The Association

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ELECTRONIC STROBOSCOPES, TACHOMETERS, AND FLASH-LAMPS.

By F. G. SPREADBURY, A.M.Inst.B.E.

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By F. G. Spreadbury, A.M.Inst.B.E.

By means of stroboscopic phenomena invaluable information may be obtained of mechanisms or bodies, the motions of which are normally such that they are incapable of distinct perception by the eye. This information results from the property that a stroboscope has of causing a moving object to appear stationary, or, alternatively, causing the motion to appear so slow that it may be easily followed. In addition to these assets, the stroboscope is capable of accurately determining the speed of a rotating body without a mechanical connection existing between the latter and the measuring instrument. Obviously this is a great advantage when either the body is difficult of access, or a normal contact type of tachometer would create an undesirable load.

Before the introduction of electronic stroboscopes and tachometers, the foregoing effects were obtained from mechanical stroboscopes which virtually consisted of a periodically operated shutter. Where a single recorded shot of a moving mechanism was required, the shutter operated once only and a lens and photographic plate or film replaced the eye; *i.e.* the stroboscope became identical with a camera. Considering the visual observation of a rotating or reciprocating mechanism by means of a periodically operating shutter, the latter is interposed between the eye and the mechanism and briefly opened and closed once per revolution or cycle. Thus the mechanism is under observation for a fraction of a cycle per cycle, this fraction being given by

$$f = \frac{\text{Time of shutter opening}}{\text{Time of cycle}} \qquad (1)$$

If the opening of the shutter is synchronised with the mechanism (*i.e.*, if it opens at precisely the same moment in each cycle), the latter will tend to appear stationary because its position with regard to some reference point will always be the same.

In addition to having to fulfil the foregoing requirements, there are certain others which must be satisfied if a stationary effect is to be obtained. Consider the motion of a point on a reciprocating body at a distance r from the eye. If the linear velocity of this point is v, the angular velocity is $w = v/r$, and, regarding the eye

as a simple biconvex lens of focal length F, the motion of the image on the retina during a time t is

$$d = w\mathrm{F}t \tag{2}$$

If d_1 is the smallest image motion which can be tolerated without perception occurring, then

$$t = \frac{d_1}{w\mathrm{F}} \tag{3}$$

and it is evident that the time of shutter opening must not exceed t as given by (3). In the case of a body rotating at w_1 radians per second, $v = w_1 r_1$ where r_1 is the radius of any particular point. Hence $w = w_1 r_1 / r$ and

$$t = \frac{d_1 r}{w_1 r_1 \mathrm{F}} \tag{4}$$

The time for one revolution is $2\pi / w_1$ seconds and, from (1),

$$f = \frac{d_1 r}{2\pi r_1 \mathrm{F}} \tag{5}$$

Now, $d_1/\mathrm{F} = \theta$, *i.e.* the angle subtended at the eye by the motion. Hence (3), (4) and (5) may be written,

$$t = \frac{\theta}{w} \tag{6}$$

$$t = \frac{\theta r}{w_1 r_1} \tag{7}$$

$$f = \frac{\theta r}{2\pi r_1} \tag{8}$$

The smallest angle which can be resolved by the average human eye is about 1·5 minutes. Thus if a point of 1 in. radius is under observation from a distance of 12 ins., $f = 1/1200$. Under these conditions the angular motion during observation is 0·3°. Considering now the value of t in (7), let the speed of rotation be 10,000 r.p.m. Then $t = 5 \times 10^{-6}$ secs.

The foregoing considerations illustrate some of the difficulties of stroboscopic observation of high-speed phenomena. The case considered is, of course, a limiting one and, in practice, larger values of f and t may be tolerated, particularly for speed measurements. However, the necessity that t shall be small creates the difficulty of adequate illumination of the object because the intensity of the retinal impression depends both on the intensity of illumination of the object and the time of its persistence, provided the latter is below a certain value. The product of these two quantities is conveniently measured in lumen-seconds.

Two limitations of mechanical stroboscopes should now be apparent. One is the difficulty of operating shutters at very high repetition rates and the other that of obtaining adequate illumination of high-speed objects which it is desired to observe. A third limitation of all stroboscopes must be mentioned. After the shutter has closed, the visual impression persists for a time which varies with different individuals but which may be taken as about 0·1 sec. Hence if the repetition rate of the shutter (or impression) falls below about 600 operations per minute, an unpleasant flickering sensation is experienced. It follows that stroboscopic observation is generally unsatisfactory at frequencies less than 600 per minute, and that stroboscopic tachometers are unsuitable for measuring speeds lower than 600 r.p.m.

Electronic Stroboscopy.

With mechanical stroboscopes, while the shutter is open, the moving object is seen either by reflected daylight or some steady source of artificial illumination. Provision is usually made for screening the eyes from any other illumination, an eyeshade or hood being provided for this purpose. Thus, until the shutter opens, the eyes are in darkness. It follows that on opening the shutter the ratio of the two illumination intensities is infinite. For effective stroboscopy, however, a change of this character is not essential. In practice a finite ratio will produce a stroboscopic effect, provided the ratio is sufficiently high. Furthermore, the change in illumination intensity may be continuous. Thus, the slight periodic variations in the light output of a metal filament lamp, when operated from an A.C. supply, are sometimes employed to determine, stroboscopically, the speed of a gramophone turntable.

Because of the relatively large thermal capacity of the filament of an incandescent lamp, the variations in the light output with A.C. operation are too small to be of much practical importance. However, it is well-known that pronounced stroboscopic effects may occur with gaseous discharge lamps. This is because such lamps are not thermal radiators and, therefore, do not continue to emit light after the current is removed. Thus, changes in current are followed by practically instantaneous changes in light output, from whence arise the stroboscopic effects when these lamps are operated from an alternating current supply.

A factor increasing the stroboscopic effect of a discharge lamp is that, under certain conditions, the lamp current does not persist for a full half cycle. Generally, discharge lamps will not conduct until a certain voltage, termed the striking potential or voltage, is applied. They also extinguish at a further voltage, termed the extinction voltage. The extinction voltage is usually somewhat lower than that of striking and, during conduction, the lamp voltage

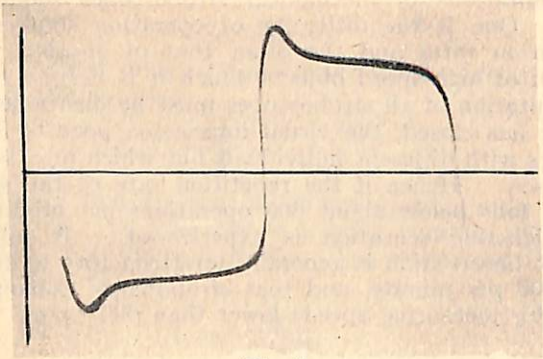


Fig. 1.

is roughly constant at a value somewhat intermediate between the two. This is exemplified by Fig. 1, which shows the lamp voltage waveform of a 125 watt mercury vapour lamp. Let a lamp with such characteristics be connected in series with a non-inductive resistance to a sinusoidal supply voltage. The supply voltage will increase from zero until the lamp striking voltage v_s is reached. The lamp voltage will then fall to v_e and a current will flow given by

$$i = \frac{V \sin pt - v_e}{R}$$

where V sin pt is the supply voltage and R is the series resistance. The moments at which conduction respectively commences and ceases are given by

$$pt_1 = \text{arc sin } \frac{v_s}{V} \qquad (9)$$

$$pt_2 = \text{arc sin } \frac{v_e}{V}$$

where v_e is the extinction voltage. Hence two current pulses occur per cycle, the fraction which each is of a half-cycle being

$$\frac{\pi - (pt_1 + pt_2)}{\pi}$$

$$= 1 - (pt_1 + pt_2) / \pi$$

$$= 1 - \frac{2}{\pi} pt_1 \qquad (10)$$

if $v_e = v_s$. It is evident that the nearer pt_1 becomes to $\pi/2$ the more pronounced will be the stroboscopic effect, because the light pulses become of shorter duration.

From (10) it would appear that if pt_1 could be made small and a lamp fed from a variable frequency supply, a practical form of stroboscope would result. However, in general, this is not so, because v_e and v_s are subject to variations. Because of such limitations, electronic stroboscopes invariably employ special discharge lamps, the operating frequency of which is precisely controlled by special circuits. As the field required to be illuminated by a stroboscope (or flash lamp) is, generally, small, stroboscope lamps are compact in construction and are housed in some form of reflector. From what has been said previously concerning the general principles of stroboscopy, it follows that such lamps give very intense illumination for very short time periods. This is effected by suddenly discharging a condenser, charged to a high voltage, through the lamp without any intentional impedance interposed between lamp and condenser. That is, the lamp virtually short-circuits the condenser. It will be appreciated that by this means very large currents may be obtained acting for very short periods. The magnitude of these currents and periods will be given when discussing specific types of stroboscope lamps.

It has been stated that a finite ratio of the maximum to minimum illumination intensity of a periodically varying light source may be adequate for effective stroboscopy. Thus it is quite possible to produce satisfactory stroboscopic effects against a background of normal interior lighting, whether this be natural or artificial. If the character of the stroboscopic light source is similar in character to daylight (as is the case with the high intensity lamps to be shortly described) then the maximum intensity of the source must be relatively high. However, if the character is dissimilar, a lower intensity may be employed. This is the case with neon-filled lamps because of their distinctive colour. Thus, with a neon-filled stroboscopic lamp, satisfactory results may be obtained with an average illumination intensity of one foot-candle against a background illumination intensity of 100 foot-candles of natural lighting.

The Strobotron and Neostron Lamps.

A lamp which has been specifically developed for stroboscopic work and speed measurement is the Strobotron, manufactured by Hygrade Sylvania. A similar lamp is the Ferranti NSP1 Neostron. These lamps are of cold-cathode, tetrode, construction, typical examples being indicated by Figs. 2 and 3. Considering Fig. 2, it will be noted that the electrodes consist of cathode, anode, and two grids, the latter being relatively close together. G_1 is the control grid and G_2 the screen grid. The anode is approximately 2·5 cms. distant from the upper edge of G_2. The cathode consists

of either a cup or a gauze sac, containing a cesium compound, and, in the Strobotron, is surrounded by a ceramic insulator. The function of the latter is to concentrate the discharge on to the active portion of the cathode, this liberating free cesium and resulting in high thermionic emission. The control grid is formed of wire gauze, or a simple rectangular plate, and is mounted immediately above the cathode. During operation the grid becomes coated with cesium and this has the effect of lowering the breakdown voltage of the lamp, should G_1 be employed as a cathode. The screen grid consists of a flanged tube coated with graphite. Cesium is deposited on this grid also, but the graphite has the effect of preventing a lowering of the breakdown voltage between G_2 and the cathode. As shown by Fig. 2, the anode support is enclosed by a glass tube, the latter preventing the discharge from occurring on the support rather than the anode. The gas-filling of the lamp is neon, and the lamp design is such that short-period, high-current discharges may be arranged to occur up to 300 cycles per second. The discharge period varies from 10 to 100 microseconds and the discharge current

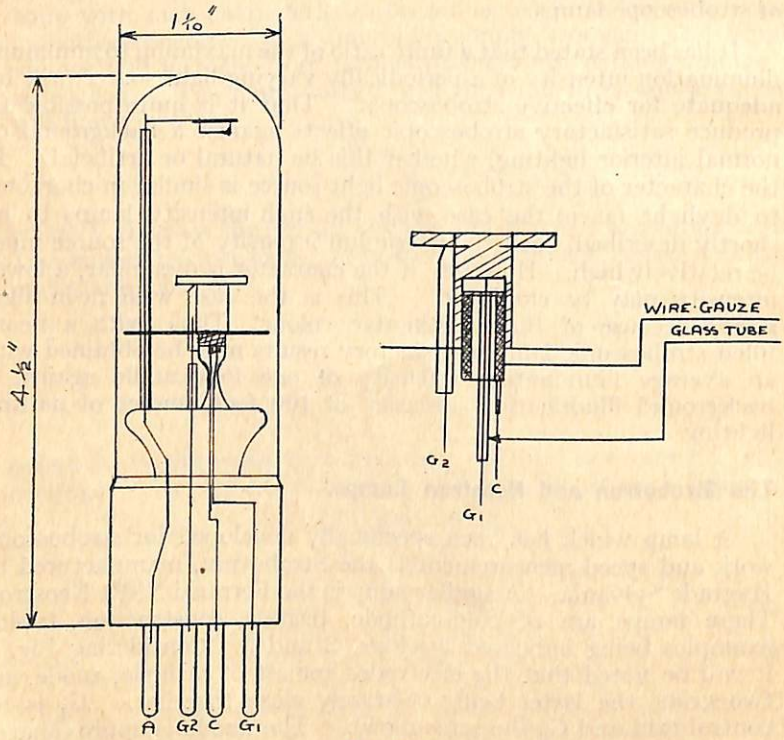


Fig. 2.

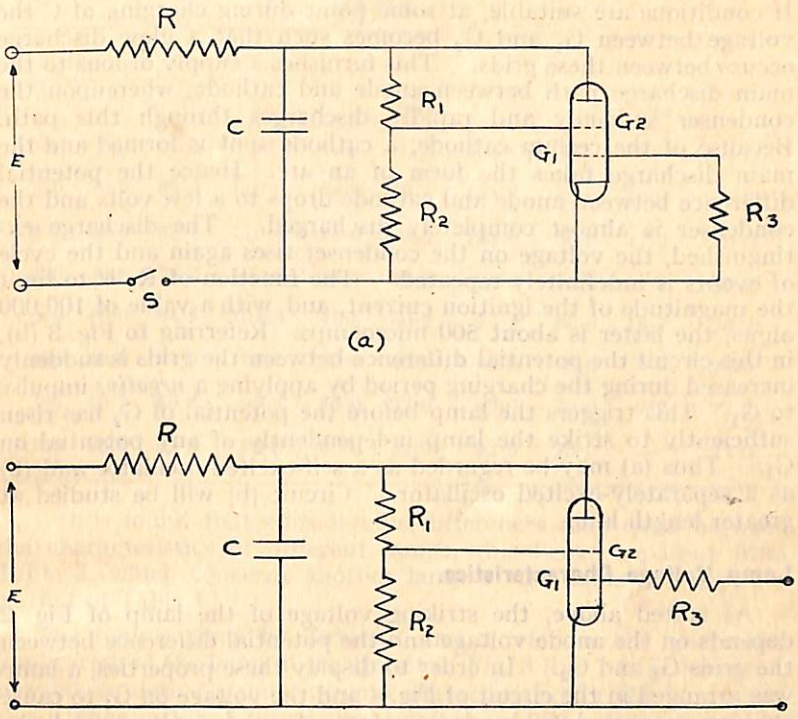


Fig. 3.

may reach 200 to 300 amperes. It will be readily appreciated that a lamp with these characteristics is very suitable for stroboscopic work.

The lamp generally works in conjunction with a resistance-capacitance circuit, as described on page 18, and its performance largely depends on the potential difference between the grids G_1 and G_2. Two circuits are commonly employed for operating the lamp, these being shown by Fig. 3, (a) and (b). The principle of (a) is fully explained on page 19. Here it may be stated briefly that on closing the switch S the voltage across C rises exponentially and, provided the lamp does not strike, will ultimately become steady at a value equal to E. With the potentiometer arrangement shown, it is evident that the screen potential is always a constant fraction of the anode potential. As the voltage on C increases so also does the potential difference between G_1 and G_2.

If conditions are suitable, at some point during charging of C the voltage between G_1 and G_2 becomes such that a glow discharge occurs between these grids. This furnishes a supply of ions to the main discharge path between anode and cathode, whereupon the condenser suddenly and rapidly discharges through this path. Because of the cesium cathode, a cathode spot is formed and the main discharge takes the form of an arc. Hence the potential difference between anode and cathode drops to a few volts and the condenser is almost completely discharged. The discharge extinguished, the voltage on the condenser rises again and the cycle of events is indefinitely repeated. The function of R_3 is to limit the magnitude of the ignition current, and, with a value of 100,000 ohms, the latter is about 500 microamps. Referring to Fig. 3 (b), in this circuit the potential difference between the grids is suddenly increased during the charging period by applying a *negative* impulse to G_1. This triggers the lamp before the potential of G_2 has risen sufficiently to strike the lamp independently of any potential on G_1. Thus (a) may be regarded as a self-excited oscillator and (b) as a separately-excited oscillator. Circuit (b) will be studied at greater length later.

Lamp Voltage Characteristics.

As stated above, the striking voltage of the lamp of Fig. 2 depends on the anode voltage and the potential difference between the grids G_1 and G_2. In order to display these properties, a lamp was arranged in the circuit of Fig. 4 and the voltage on G_1 to cause striking measured for various values of anode voltage and the ratio R_1/R_2. The results obtained are shown by Table 1.

It will be noted that as the anode voltage (and that of G_2) increases, the voltage on G_1 necessary to cause striking decreases. Also, $G_1 + G_2$ decreases, although at a much slower rate than

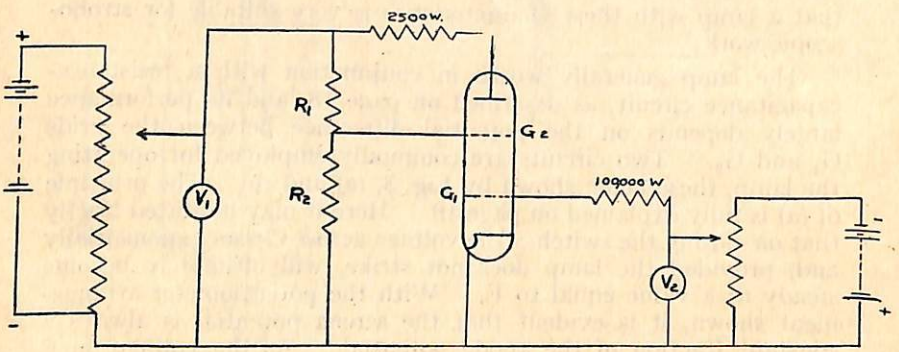


Fig. 4.

TABLE 1.

R_1/R_2	5 : 1			4 : 1			3 : 1		
	Volts.			Volts.			Volts.		
Anode	G_2	G_1	G_1+G_2	G_2	G_1	G_1+G_2	G_2	G_1	G_1+G_2
180	30·0	89·9	119·9	36·0	68·8	104·8	45·0	49	94·0
200	33·0	83·4	116·4	40·0	63·0	103·0	50·0	41·7	91·7
220	36·6	73·2	109·8	44·0	54·6	98·6	55·0	30·2	85·2
240	40·0	64·5	104·5	48·0	46·2	94·2	60·0	18·2	78·2
260	43·3	52·9	96·2	59·0	40·5	99·5	65·0	9·0	74·0
280	46·7	46·8	93·5	56·0	37·0	93·0	70·0	2·2	72·2
300	50·0	43·8	93·8	60·0	32·9	92·9	75·0	—	72·0

G_1. It is found that considerable differences may exist between the characteristics of different lamps, this being apparent from Table 2, which concerns another lamp of the same manufacture as that of Table 1.

The figures given by Tables 1 and 2 refer to the particular application of the lamp in the circuit of Fig. 3 (b). It is, however, possible to derive a more general characteristic for the lamp, and this is done in Fig. 5 for an anode voltage of 300 volts. It will be noted that it is possible to trigger the lamp with either a positive

TABLE 2.

R_1/R_2	5 : 1			4 : 1			3 : 1		
	Volts.			Volts.			Volts.		
Anode	G_2	G_1	G_1+G_2	G_2	G_1	G_1+G_2	G_2	G_1	G_1+G_2
180	30	99	129	36·0	95·0	131·0	45	75·0	120·0
200	33	91·8	124·8	40·0	85·5	125·5	50	64·4	114·4
220	36·6	83·8	120·4	44·0	76·0	120·0	55	52·0	107·0
240	40·0	78·8	118·8	48·0	70·8	118·8	60	41·5	101·5
260	43·3	76·0	119·3	52·0	66·8	118·8	65	35·5	100·5
280	46·7	72·8	119·5	56·0	63·0	119·0	70	29·8	99·8
300	50·0	72·0	122·0	60·0	59·0	119·0	75	21·0	96·0

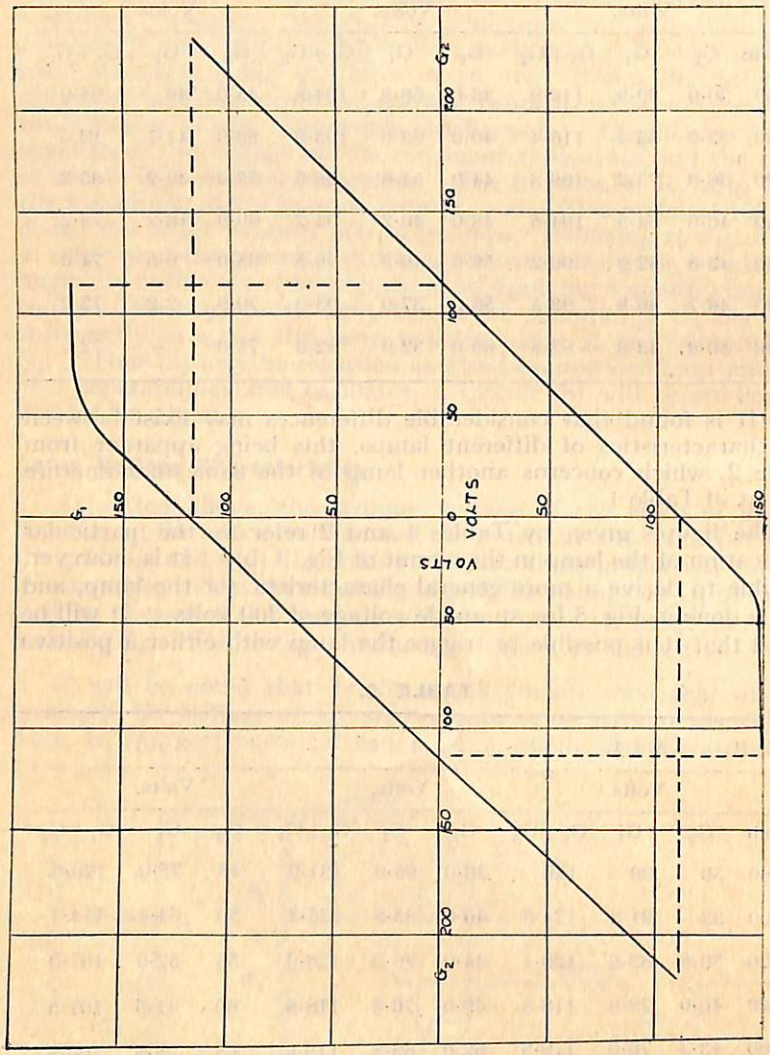

G1
150
100
50
0
VOLTS
50
100
150
G2
200
150
100
50
0
VOLTS
50
100
150
200
G2

Fig. 5.

or negative potential on either the screen or grid. Generally speaking, those parts of the characteristic lying within the second and fourth quadrants are the most important. On these parts, either the screen or grid potentials may be applied first without a discharge occurring. Considering the upper part of the characteristic in the first quadrant, the potential must, of course, be first applied to G_2. Triggering is then produced by applying an appropriate potential to G_1. Regarding the lower part of the characteristic, here the potential must be first applied to G_1. Similar considerations apply to the third quadrant.

Life.

The life of these lamps depends, of course, on their conditions of operation. The conditions are concerned with the values of the discharge current, average current, anode voltage, and frequency of operation. The normal maximum frequency has already been indicated and, in the case of the Neostron, the anode voltage should not exceed 450 volts. Under the usual conditions of use, the life is about 250 hours. During operation cesium may be deposited on both the grids with a consequent modification of the characteristics of the lamp. In practice, the author finds that, with continued use, the potential difference between G_1 and G_2 to cause triggering may become so low as to cause circuit (*b*) to revert to a self-excited oscillator. This may be remedied by lowering the screen potential.

In addition to the NSP1 lamp, already mentioned, several other similar types are available. These are the Ferranti ASP1, NSPT and ASPT types. The last two will operate at a maximum anode voltage of 750 volts. The letter A denotes that the lamps are argon-filled. These lamps give a blue glow and are more suitable for photography than are those filled with neon.

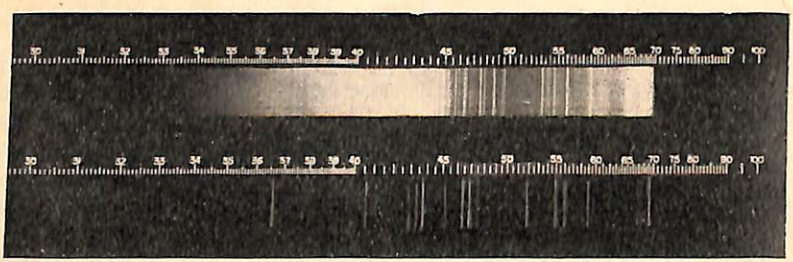
Flash Discharge Lamps.

The Neostron and Strobotron lamps are suitable for observation of moving objects only at fairly close range, as is evident from the illumination intensity curves of Fig. 45. For high intensity illumination, other lamps have been developed which are also suitable for high-speed photography. In the latter case photography is usually effected by a single flash of the lamp rather than by the apparently stationary effect produced by a lamp operating from a multi-flash circuit. These lamps are similar to the Strobotron in that the discharge rapidly passes from a glow to an arc. The cathodes are formed from mixtures of metals, of which at least one has a low work function. The discharge current and arc loading are of a very high order, and this leads to high brightness and luminous efficiency. As with the Strobotron, the discharge

is produced by the lamp virtually short-circuiting a condenser. Flash discharge lamps are of diode construction and are usually triggered by a third external electrode. The latter generally consists of a wire wound round the outside of the lamp. The discharge condenser is of relatively large capacity and is frequently charged to several thousand volts prior to triggering. As an example of the electrical characteristics of these lamps, let the condenser be of 100 μ F capacity and charged to 2000 volts. The energy content is thus $\frac{1}{2}CV^2 = 200$ joules. Assuming this energy to be discharged in 100 microseconds, the average rate of energy dissipation in the lamp is $200/100 \times 10^{-6} = 2000$ kilowatts. If it be assumed that the average discharge voltage is half the initial voltage, *i.e.* 1000 volts, the average discharge current is 2000 amperes. With a luminous efficiency of 75 lumens per watt, the luminous power is $1{\cdot}5 \times 10^8$ lumens and the light output $1{\cdot}5 \times 10^4$ lumen-secs. The brightness would probably be of the order of 5×10^4 stilbs.* The phenomenal characteristics of these lamps undoubtedly justify the Americanism, "bottled lightning." A further important characteristic is the complex spectra which are produced. This is the case for practically all gas fillings, although argon, krypton, or zenon, or a krypton-zenon mixture, is usually employed. The spectra are such that the light approximates to northern daylight with a colour temperature of about 6500°K. Fig. 6 shows spectrograms of the same lamp operating under two conditions. The approximation to a continuous spectrum under flash conditions is evident.

Lamp Design.

Except for what is known as the "open spiral" lamp, flash discharge lamps are designed to break down at a voltage considerably higher than that to which the discharge capacitance is normally charged. Thus, with an initial capacitance voltage of



Spectrum of Krypton due to:— (1) Condenser Discharge.
(2) Low Current Discharge.

Fig. 6.

(By courtesy of Siemens Electric Lamps and Supplies Ltd.).

*One stilb = one candle power per sq. cm.

2000 volts, the triggering voltage may be as high as 15,000 volts. The gas filling is at a low pressure so that, apart from their flash characteristics, the lamps may be regarded as of the glow type. The extinction voltage is as low as possible in order that the condenser may discharge the maximum possible energy. Because of the extremely high discharge currents, special precautions must be taken in the design of the lamp seals and envelope. Thus the highest loads are withstood by a quartz envelope and correspondingly lower loads by hard and soft glasses. However, even with lime soda glass, current densities of 1000 amps. per sq. in. may be safely withstood in a single flash. Where the lamps are employed for purely stroboscopic work, *i.e.*, in multi-flash circuits, lower instantaneous loadings are necessary because of the higher average loading.

The time order of the discharge has been previously stated. However, the discharge time may be controlled to some extent by the value of the condenser capacity, as is indicated by (33). There is a maximum current which a given lamp will pass and any attempt to pass a larger current merely results in an increase in the discharge time. It follows that for very high speed work it is

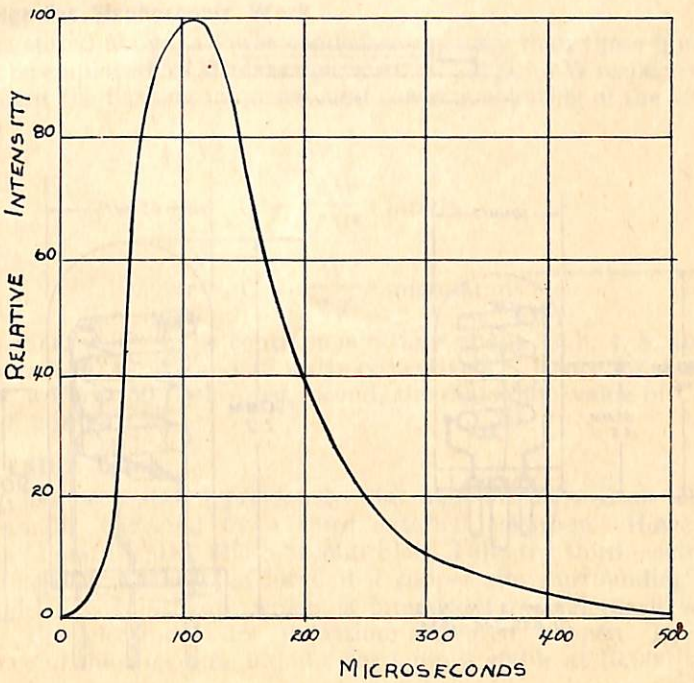


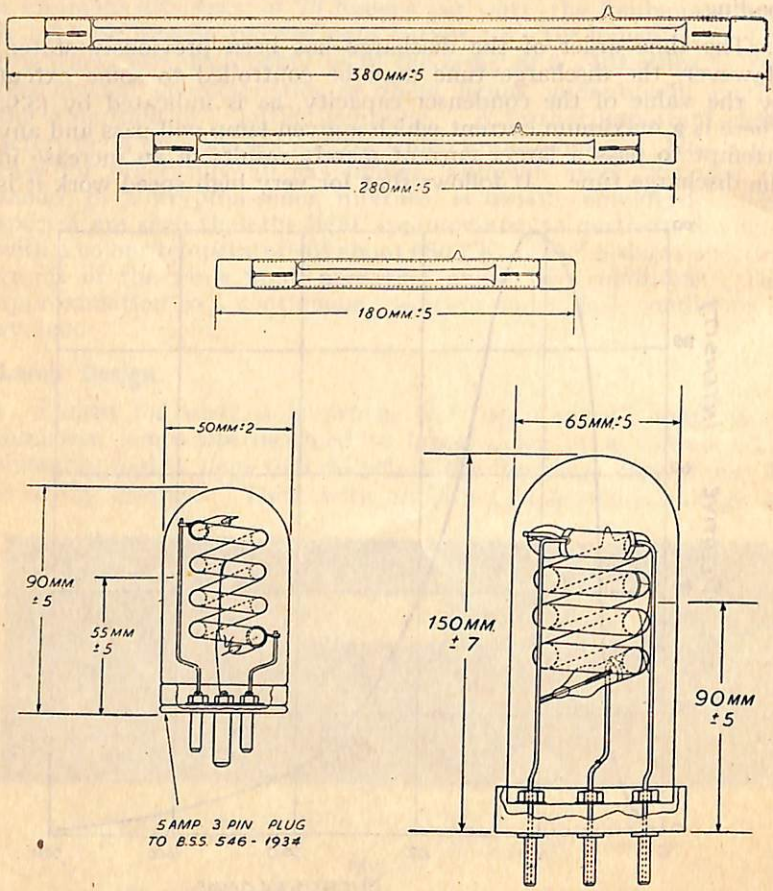
Fig. 7.

necessary to limit the quantity of electricity in each discharge. With suitable design and conditions, single flashes of one micro-second duration may be obtained. In stating the value of the discharge time it must be understood that this refers to an effective value. In practice, the light intensity rises rapidly to a maximum and then dies away more slowly, a typical example being shown by Fig. 7.

A statement of the discharge time largely ignores the lower parts of the curve, particularly the tail.

Lamp Form.

Various shapes are given to high-speed discharge lamps, but in general the design is such that they are compact in form. This is



(By courtesy of Siemens Electric Lamps and Supplies Ltd.).

Fig. 8.

necessary in order that the light may be limited to a comparatively small solid angle by some optical system. In the case of the Strobotron and Neostron, the lamp in form and size is similar to that of a small receiving valve, as is evident from Fig. 2. The high-discharge lamps are, usually, either straight or spiralled tubes, as shown by Fig. 8, which concerns several Siemens' Sieflash lamps.* Referring to Fig. 8, the S.F.2 lamp consists of a hard glass tube, giving an effective light source approximately 4·5 cm. × 5·5 cm. The lamp may be operated from a 100 μ F condenser charged to 2000 volts. The S.F.3 lamp may be operated at 2000 volts from a 50 μ F condenser. The S.F.4, 5, and 6 lamps may be operated at 2000 volts, respectively, from 100 μ F, 60 μ F, and 30 μ F condensers. The given operating voltages and capacities refer to single flash operation only. For multi-flash, *i.e.*, stroboscopic, work the condenser capacity must be reduced in order to avoid overloading.

Single-flash lamps of the types shown by Fig. 8 have remarkable photographic properties to which more detailed attention will be given later. Here it may be said that with the S.F.2 type, operating from 100μF charged to 2000 volts, a satisfactory negative may be obtained at 50 feet from the object with a lens aperture of f.11.

Ratings for Stroboscopic Work.

As stated above, a lower condenser capacity than those quoted must be employed for stroboscopic work. Let f and W respectively represent the flashing frequency and continuous rating of the lamp. Then

$$\tfrac{1}{2}\,CV^2 f = W$$

$$\text{and} \quad C = \frac{2W}{f\,V^2} \quad \text{farads.}$$

$$\text{or} \quad C = \frac{W}{2f} \quad \text{microfarads}$$

if V = 2000 volts. The continuous ratings of the SF.3, 4, 5, and 6 lamps are 30, 40, 26, and 13 watts respectively. Hence for stroboscopic work at 50 flashes per second, the maximum value of C for the SF.3 is 0·3 μ F.

The LSD.2 Lamp.

It has been stated previously that high intensity flash lamps are usually triggered by a third external electrode. However, in the Mullard LSD.2 Micro-Second Flash Tube the third electrode is internal and takes the form of a copper ring surrounding the cathode. In this lamp, which is intended for single-flash work only, the electrodes are potassium-activated copper. In the absence of the triggering impulse the lamp is stable at 10,000 volts

*The linear lamps are, respectively, in decreasing order of length, the S.F.4, S.F.5 and S.F.6. The smaller of the spiral lamps is the S.F.3.

and, at this voltage, triggering may be effected by an oscillatory transient of about 3000 volts on the third electrode. As its name implies, the LSD.2 lamp is intended for work of extremely short duration, a flash of approximately one microsecond being obtained from the discharge of a condenser of 3 μ F, charged to 7500 volts. Under these circumstances, the light output is of the order of 1500 lumen-seconds. The tube is linear in design, with an anode-cathode spacing of 30 mm. The gas filling is mainly argon.

The Open-Spiral Lamp.

The lower two of the lamps shown by Fig. 8 are sometimes termed "closed-spiral" lamps. In such lamps the outer glass envelope is intended for protective purposes only. In what are known as "open-spiral" lamps* the spiral is fitted in a sealed envelope, one end of the spiral being closed and carrying an electrode. The other end of the spiral opens into the envelope, the latter containing the other electrode. It will be seen that the spiral and envelope are in direct communication with each other, the gas filling being common to both. Such lamps, of course, constitute simple diodes and must be employed in circuits such as those of Figs. 9 and 16.

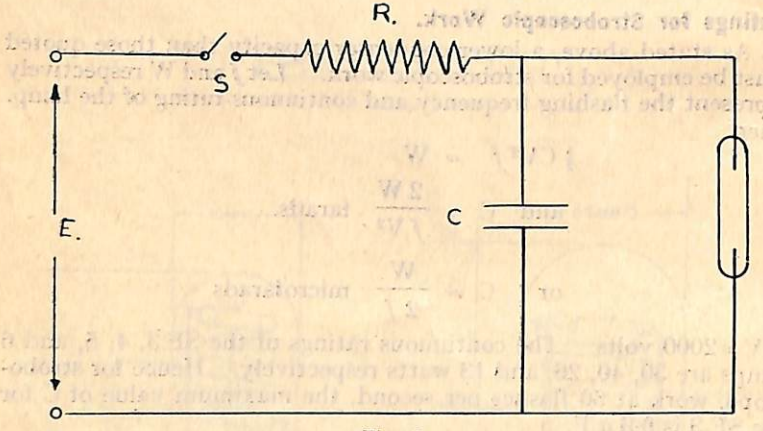


Fig. 9.

The Discharge Circuit.

The basic circuit element of practically all electronic stroboscopes (as well as single-flash lamps) is shown by Fig. 9 where a simple diode discharge lamp is connected across a condenser C. To this circuit a steady D.C. voltage, E, is applied. On closing the switch S the condenser commences to charge through R, the circuit conditions at any moment after switch closure being given by

$$Ri + v = E \qquad (11)$$

* U.S. Patent, Nos. 2,273,520, 2,281,579.

where i and v are respectively the instantaneous values of the condenser current and voltage. Writing $i = C\,dv/dt$.

$$CR\frac{dv}{dt} + v = E$$

$$\text{and} \quad \int\frac{dv}{E-v} = \int\frac{dt}{CR}$$

Integrating

$$\log_\epsilon (E-v) = -\frac{t}{CR} + \log_\epsilon K \tag{12}$$

where K is a constant. When $t = 0$, $v = 0$. Hence $K = E$ and

$$E - v = E\,\epsilon^{-t/CR}$$

$$\text{or} \quad v = E\,(1 - \epsilon^{-t/CR}) \tag{13}$$

Now assuming E is in excess of the lamp striking voltage, v_s, after a time t_s the lamp will strike. Thus

$$v_s = E\,(1 - \epsilon^{-t_s/CR})$$

$$\text{and} \quad t_s = CR\,\log_\epsilon\frac{E}{E-v_s}$$

Immediately following striking, the condenser voltage rapidly falls to v_e, the lamp extinction voltage. Alternatively it may be said that the condenser commences to discharge and continues until the discharge current falls to the lamp extinction current i_e. At this moment the lamp rapidly passes from a conducting to an insulating state and the condenser commences to recharge to the striking voltage. It is evident that once the initial curve has been traced, given by (13), it is not repeated, as the condenser voltage oscillates between the two values v_s and v_e.

Let t be reckoned as zero when $v = v_e$. Then, from (12), $K = (E - v_e)$ and

$$E - v = (E - v_e)\,\epsilon^{-t/CR}$$

$$\text{and} \quad v = E - (E - v_e)\,\epsilon^{-t/CR} \tag{14}$$

After an interval t_1, $v = v_s$. Hence

$$t_1 = RC\,\log_\epsilon\frac{E - v_e}{E - v_s} \tag{15}$$

If the discharge time of the condenser is negligible compared with the charging time, as it normally is, then

$$f = \frac{1}{t_1} = \frac{1}{RC\,\log_\epsilon\dfrac{E - v_e}{E - v_s}} \tag{16}$$

This gives the frequency of the oscillation and, of course, the flashing frequency of the lamp. Evidently f may be varied by

varying either R, C or E. In practice, R is generally the variable. The waveform of the voltage on C is indicated by Fig. 10, a typical oscillogram, when v_e is very small, being shown by Fig. 36.

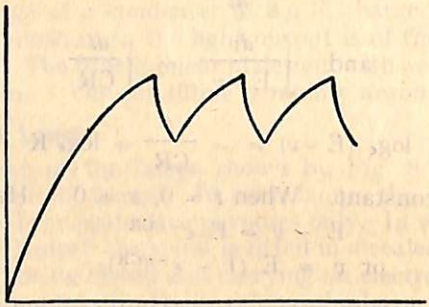


Fig. 10.

As an alternative to the resistance of Fig. 9, the condenser may be charged by the anode current of a pentode. In this case, provided the knee of the anode characteristic is not approached, the condenser will be charged at approximately constant current, the value of the latter being variable by means of variation in either the potentials of the screen or control grid. If I is the value of the constant charging current, then

$$It_1 = C\ (v_s - v_e)$$

$$\text{and } t_1 = \frac{C\ (v_s - v_e)}{I}$$

$$f = \frac{I}{C\ (v_s - v_e)}$$

Charging Current.

The condenser charging current is given by Cdv/dt and, from (13),

$$i = \frac{E}{R}\ \epsilon^{-t/CR}$$

Thus, in the case of a single-flash circuit, the supply must be capable of delivering a maximum current of value equal to E/R at a voltage E. The rating of the charging resistance must also be such as to carry safely this current.

In a multi-flash circuit, from (14),

$$i = \frac{E - v_e}{R}\ \epsilon^{-t/CR}$$

The average value of the charging current is

$$i_{av} = \frac{1}{t_1}\int_0^{t_1} i\,dt = \frac{E - v_e}{t_1 R}\int_0^{t_1} \epsilon^{-t/CR}\,dt$$

$$= \frac{C\,(E - v_e)}{t_1}\,(1 - \epsilon^{-t_1/CR})$$

where t_1 is given by (15). Substituting for t_1

$$i_{av} = \frac{v_s - v_e}{R \log_\epsilon \dfrac{E - v_e}{E - v_s}} \qquad (17)$$

and this current in conjunction with E gives the supply rating.

In order to determine the rating of the charging resistance, it is necessary to find the r.m.s. value of the current. This is given by

$$\sqrt{\frac{1}{t_1}\int_0^{t_1} i^2 dt} = \frac{E - v_e}{R}\sqrt{\frac{1}{t_1}\int_0^{t_1} \epsilon^{-2t/CR}\,dt}$$

$$= \frac{E - v_e}{R}\sqrt{\frac{CR}{2t_1}}\,(1 - \epsilon^{-2t_1/CR})$$

Substituting for t_1

$$i_{r.m.s.} = \frac{1}{R}\sqrt{\frac{[\,(E - v_e)^2 - (E - v_s)^2\,]}{2 \log_\epsilon \dfrac{E - v_e}{E - v_s}}} \qquad (18)$$

It will be noted that both (17) and (18) are independent of C and vary inversely as R. This is the case in practice. The form factor of the current is

$$\frac{i_{r.m.s.}}{i_{av}} = \frac{1}{\sqrt{2}\,(v_s - v_e)}\sqrt{[\,(E - v_e)^2 - (E - v_s)^2\,] \log_\epsilon \frac{E - v_e}{E - v_s}} \qquad (19)$$

However, in practice, (19) generally differs but little from unity.

Efficiency of Charge.

The efficiency with which the condenser is charged may be obtained as follows. During charging, the rate at which energy is supplied by the source is Ei. The rate of energy storage by C is iv. Hence the charging efficiency is

$$\eta = \frac{\int iv\,dt}{\int Ei\,dt}$$

where the time limits of the two integrals are the same. But $i = C dv/dt$ and

$$\eta = \frac{\int_0^{v_1} v\,dv}{E\int_0^{v_1} dv}$$

$$= \frac{v_1}{2E} \qquad (20)$$

where v_1 is the voltage to which the condenser is charged. It is evident that the maximum charging efficiency is 50 per cent.

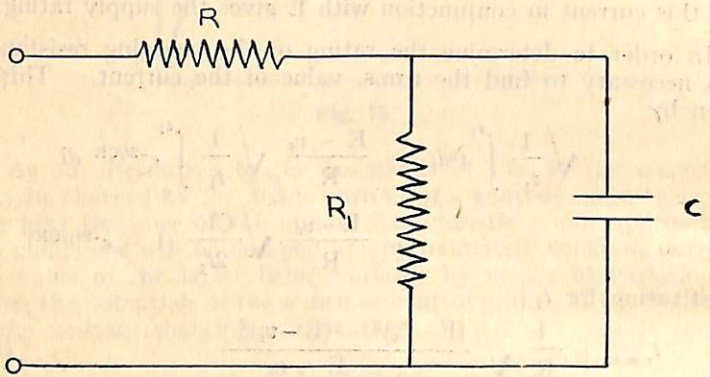


Fig. 11.

For employment with a Neostron or Strobotron lamp, it is necessary to shunt the condenser of Fig. 9 with a resistance R_1, to provide the necessary voltage for the screen. The circuit now becomes that of Fig. 11, where i_1 and i_2 are respectively the currents in R_1 and C. The circuit equations are

$$Ri + R_1 i_1 = E \qquad (21)$$
$$i_1 + i_2 = i$$
$$i_2 = C\frac{dv}{dt}$$
$$i_1 = v/R_1$$

Substituting in (21)

$$R\left(\frac{v}{R_1} + C\frac{dv}{dt}\right) + v = E$$

$$\frac{R}{R_1}v + RC\frac{dv}{dt} + v = E$$

$$CR\frac{dv}{dt} + \left(\frac{R + R_1}{R_1}\right) v = E$$

$$\text{or} \quad CR\frac{dv}{dt} + av = E$$

$$\text{and} \quad \int \frac{dv}{E - av} = \int \frac{dt}{CR}$$

Integrating

$$\log_\epsilon (E - av) = -\frac{at}{CR} + \log_\epsilon K$$

When $t = 0$, $v = 0$. Hence $K = E$, and

$$E - av = E\epsilon^{-at/CR}$$

$$\text{or } v = \frac{E}{a}(1 - \epsilon^{-at/CR})$$

$$= \frac{E}{1 + R/R_1}\left(1 - \epsilon^{-\frac{1 + R/R_1}{CR}t}\right) \tag{22}$$

If $R_1 \to \infty$ then (22) reduces to (13).

It will be noted that, compared with the conditions expressed by (13), in the present case the condenser voltage builds up more slowly towards a lower final voltage, the latter being $E/(1 + R/R_1)$. However, R_1 is usually very much larger than R and thus has, generally, a small effect on the circuit conditions.

Value of R.

Mention has been made of the extinction current of a discharge lamp, *i.e.* the current below which the lamp will not conduct. An effect of this is to set a low limit to R, the charging resistance. Below this limit a multi-flash circuit will not oscillate, the lamp burning steadily. With a single-flash circuit the lamp continues to burn after the condenser discharge has occurred, although, generally, with a relatively low intensity. Considering the multi-flash circuit, at the moment the lamp is about to extinguish the voltage across R is approximately equal to $(E - v_e)$ volts. The current in R is $(E - v_e)/R$ amps. and if this current is equal to, or less than, i_e, extinction of the lamp occurs. Hence for oscillations to occur,

$$R > \frac{E - v_e}{i_e} \tag{23}$$

Similar considerations are applicable to the single-flash circuit except that (23) is the criterion for extinction to occur.

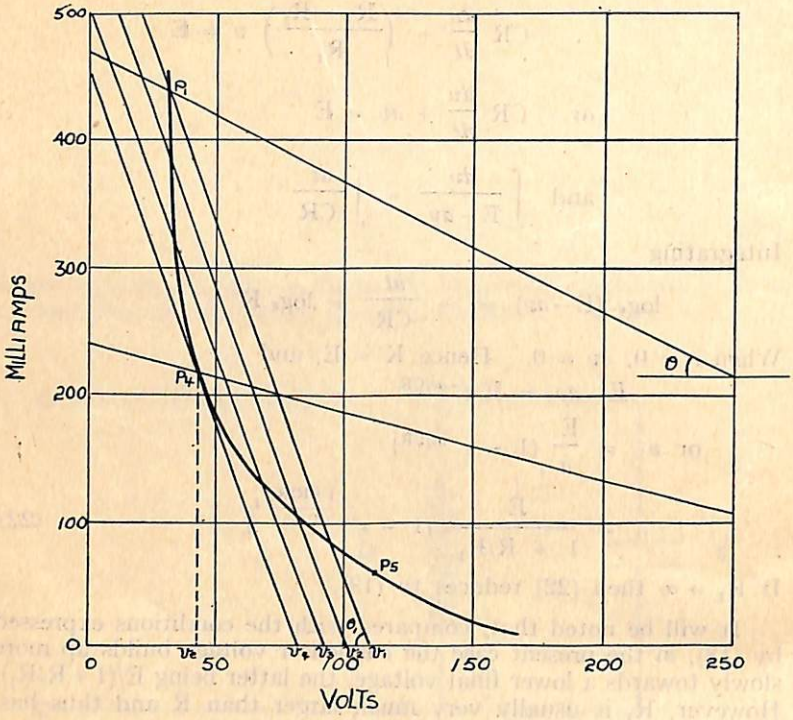


Fig. 12.

Value of i_e.

In order to determine i_e, let Fig. 12 represent the volt/ampere characteristic of a discharge lamp of the arc-forming type. Then with the lamp burning steadily the charging and discharging currents are equal, this being tantamount to saying that the voltage on the condenser is stationary. Under these circumstances the operating point is determined by the load line, $(R + r) = \cot \theta$, at its point of intersection with the characteristic. Through this point a second load line may be drawn, $r = \cot \theta_1$, the difference in the voltages on the condenser and lamp terminals being equal to ir, where i is the lamp current and r is the value of any resistance between the condenser and lamp. Regarding the condenser as the source of the lamp current, if v_1 is the condenser voltage at any particular instant, the operating point on the characteristic may be determined at this instant by drawing a load line from the point v_1, as in Fig. 12. Now as the condenser continues to discharge and its voltage to fall, the load line will move parallel to itself occupying successive positions, some of which are shown by v_2

and v_3. If conditions are suitable, a position will finally be reached at which the load line is tangential to the characteristic, as at v_4. At this point lamp extinction starts to occur, v_4 rapidly falling to v_e. It will be appreciated that the value of i_e depends on the slope of the load line, as does also that of $v_,$. Considering the value of R to secure extinction, it is evident that at the point P_4, the load line corresponding to $R + r$ must pass through this point. Should it pass through P_1, a stable condition would exist, extinction failing to occur. Passing through P_5, extinction, of course, still occurs.

From the foregoing it is evident that two important factors governing the behaviour of the discharge circuit are the values of R and r. For stroboscopic work the value of C is relatively high and, as the frequency of operation seldom exceeds 250 c.p.s., it follows from (15) that the value of R tends to be low. Hence, to secure extinction and oscillatory conditions, it is evident from Fig. 12 that the value of r must also be low. It will shortly be shown that for other reasons it is desirable that r should be small. Hence, in practice, the value of r is usually that of the leads connecting the condenser to the lamp. In these circumstances it is evident that $v_4 \fallingdotseq v_e$, Fig. 12. If v_e is small compared with E, it will be noted from (23) that

$$R > E/i_e$$

The characteristic of Fig. 12 concerns a Neostron lamp and from this, with the value of r confined to that of the lamp leads, it will be seen that i_e must be relatively high. Thus a low value of R may be employed. For example, in the stroboscope of Fig 32 the value of R is 2500 ohms.

If experiments are made with a glow lamp of the Osglim type it will be found that the value of R to produce an oscillatory state is relatively high. This is due to the nature of the characteristic and the low extinction current. Fig. 13 shows a characteristic determined by the author. It will be noted that a voltage minimum exists at 0·5 Ma. If the value of r is negligible, then the load line corresponding to this quantity is perpendicular as shown. To obtain extinction, the load line corresponding to R must either pass through or below the voltage minimum and hence the least value of R to secure extinction is 0·25 megohm. On employing the lamp of Fig. 13 in a circuit of the type shown by Fig. 9, it was found that for resistance values less than about 0·25 megohm oscillations did not occur.

Light Output.

The output of the lamp depends on the energy discharged by the condenser at each flash. This energy is

$$J = \tfrac{1}{2} C (v_s^2 - v_e^2) \text{ joules} \qquad (24)$$

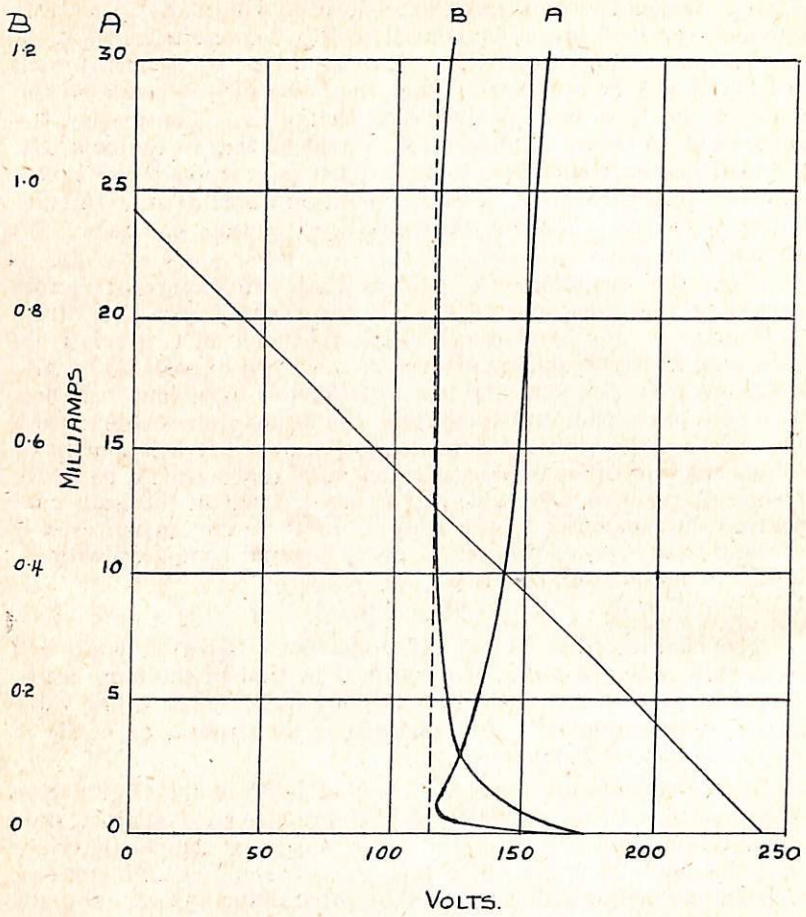


Fig. 13.

For a given value of v_s it is evident that the discharge and light energy are larger the smaller v_e becomes. Hence it is desirable that the lamp extinction voltage should be as low as possible. In glow discharge lamps the ratio v_s/v_e is relatively small compared with that of a lamp in which the discharge starts as a glow and passes to an arc. Thus, in the latter case, v_s is that of a glow while v_e is of the order of the volt drop across an arc, *i.e.* about 10 to 20 volts. In lamps of the Neostron type, v_e is usually so small compared with v_s that it may be neglected. Thus, in this case,

$$J = \tfrac{1}{2} C v_s^2$$

The stroboscope of Fig. 32 employs a Neostron which, for low frequencies, is struck at about 300 volts. As C in this instrument is $3\,\mu$ F,

$$J = 0{\cdot}135 \text{ joule per flash.}$$

With regard to a glow lamp of the Osglim type, in one lamp tested by the author the values of v_s and v_e were respectively 168 and 136 volts. Hence

$$J = 0{\cdot}0144 \text{ joule per flash}$$

if $C = 3\,\mu$ F. From the foregoing figures it will be appreciated that a simple glow lamp employed in the circuit of Fig. 9 generally gives too little illumination to be of much practical value.

Of the energy discharged by the condenser through the lamp, this is partly dissipated as heat and partly as light. Obviously the greater the latter the more efficient is the process of energy conversion. The equation to the volt drop across a discharge lamp may be written

$$v = v_e + \rho i \tag{25}$$

where v_e is regarded as constant and ρ is known as the dynamic or slope resistance of the lamp. If ρ is independent of i, then

$$\frac{dv}{di} = \rho \tag{26}$$

With ρ dependent on i, we must write

$$\frac{dv}{di} = f\,(i) \tag{27}$$

From (25), the instantaneous rate of energy dissipation in a lamp is

$$iv = v_e\, i + \rho\, i^2 \tag{28}$$

Now v_e may be regarded as the cathode fall of potential and thus the term $v_e\, i$ represents the purely heat converting properties of the lamp. If η_1 is the luminous efficiency, then the rate at which the condenser energy is converted to light energy is

$$\eta_1\, \rho\, i^2 \text{ lumens}$$

where η_1 is expressed in lumens per watt. From (28) it is evident that it is desirable that v_e should be small. In the case of a glow lamp v_e is relatively high; for the Osglim lamp mentioned above, 136 volts. For an arc v_e is between 10 and 20 volts. Thus a low value of this quantity not only permits the condenser to discharge a greater quantity of energy through the lamp, but also causes a larger amount of this energy to be converted to light. From these facts arises the great superiority of the arc to the glow for stroboscopic purposes.

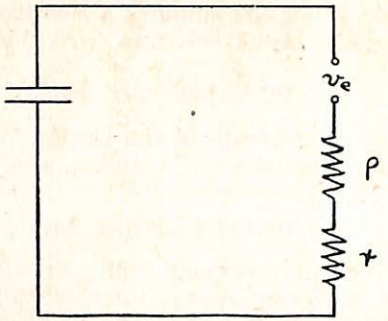


Fig. 14.

Discharge Efficiency.

The discharge circuit of a stroboscopic or flash lamp may be represented by Fig. 14, in which r represents the resistance between the condenser and the lamp. This resistance is, of course, mainly comprised by the connecting leads and, as will be shown, should be as low as possible. During a discharge we have

$$\begin{aligned} \rho i + ri - v_e + v &= 0 \\ \rho i^2 + ri^2 - iv_e + vi &= 0 \end{aligned} \tag{29}$$

and, for a complete discharge,

$$-(\rho + r)\int i^2\,dt + v_e \int i\,dt = \tfrac{1}{2} C\,(v_s^2 - v_e^2) \tag{30}$$

From (29)

$$i = -\frac{v - v_e}{\rho + r} = C\frac{dv}{dt} \tag{31}$$

$$\text{and} \quad \int \frac{dv}{v - v_e} = -\int \frac{dt}{C\,(\rho + r)}$$

Regarding ρ as constant and integrating,

$$\log_\epsilon (v - v_e) = -\frac{t}{C\,(\rho + r)} + \log_\epsilon K$$

When $t = 0$, $v = v_s$, and $K = v_s - v_e$. Hence

$$v_s - v_e = (v_s - v_e)\,\epsilon^{-t/C(\rho+r)}$$

$$\text{and} \quad v = (v_s - v_e)\,\epsilon^{-t/C(\rho+r)} + v_e \tag{32}$$

From (31)

$$i = -\frac{v_s - v_e}{\rho + r}\,\epsilon^{-t/C(\rho+r)} \tag{33}$$

the negative sign indicating that the condenser is discharging. Of course, if the condenser is initially charged to the supply voltage, E, then v_s is replaced by E. It will be noted that the maximum value of the discharge current is $(v_s - v_e) / (\rho + r)$ and increases with a decrease in r.

In order to find the energy dissipated in the lamp and the external resistance it is necessary to integrate (30). Substituting from (33) for i in the first term, and from (31) for i in the second, we have

$$-(\rho + r)\left(\frac{v_s - v_e}{\rho + r}\right)^2 \int_{\infty}^{0} \epsilon^{-2t/C(\rho+r)} + Cv_e \int_{v_e}^{v_s} vdv$$

$$\text{or } \frac{C}{2}(v_s - v_e)^2 + Cv_e(v_s - v_e) = \frac{C}{2}(v_s^2 - v_e^2)$$

In this result the first term of the left-hand member represents the energy dissipated in the slope and external resistances, while the second term represents the energy dissipated by the current flowing against an approximately constant voltage, *i.e.* the lamp extinction voltage. The energy dissipated in r is

$$\frac{r}{\rho + r}\ \frac{C}{2}(v_s - v_e)^2$$

and in ρ

$$\frac{\rho}{\rho + r}\ \frac{C}{2}(v_s - v_e)^2$$

Hence the total energy dissipated in the lamp is

$$\frac{\rho}{\rho + r}\ \frac{C}{2}(v_s - v_e)^2 + C\,v_e\,(v_s - v_e)$$

and the efficiency of discharge is

$$\eta_2 = \frac{\rho\,(v_s + v_e) + 2\,v_e\,r}{(\rho + r)\,(v_s + v_e)} \tag{34}$$

If $r = 0$, the electrical efficiency of the discharge is 100 per cent.

Again, if ρ is zero,

$$\eta_2 = \frac{2\,v_e}{v_s + v_e} \tag{35}$$

In this case, however, if the light from the negative glow is ignored, all the energy is dissipated as heat at the cathode and the luminous efficiency is zero. It may be noted that when v_e is small compared with v_s, (34) becomes

$$\frac{\rho}{\rho + r} \tag{36}$$

Influence of Inductance in Discharge Circuit.

It has so far been assumed that the discharge circuit of the condenser consists of a resistance in series with a constant voltage v_e. However, it is seldom that inductance is entirely absent, and the

effect of this must now be considered. Let the discharge circuit be represented by Fig. 15 where R_1 is the total resistance of the circuit. Then, during conduction, the circuit conditions may be expressed as

$$L\frac{di}{dt} + R_1 i + v - v_e = 0$$

or, as $i = C\,dv/dt$,

$$LC\frac{d^2v}{dt^2} + R_1 C\frac{dv}{dt} + v - v_e = 0 \qquad (37)$$

This equation has three solutions depending on the value of

$$\left(\frac{R_1^2}{4L^2} - \frac{1}{LC}\right)$$

Considering first the case when this quantity is negative, the solution of (37) is

$$v = \epsilon^{-R_1 t/2L}(A \sin wt + B \cos wt) + v_e$$

where $w = \sqrt{1/LC - R_1^2/4L^2}$, and A and B are constants.

When $t=0$, $v=E$, and $dv/dt=0$. Hence

$$v = \epsilon^{-R_1 t/2L}(E - v_e)\left(\frac{R_1}{2Lw}\sin wt + \cos wt\right) + v_e \qquad (38)$$

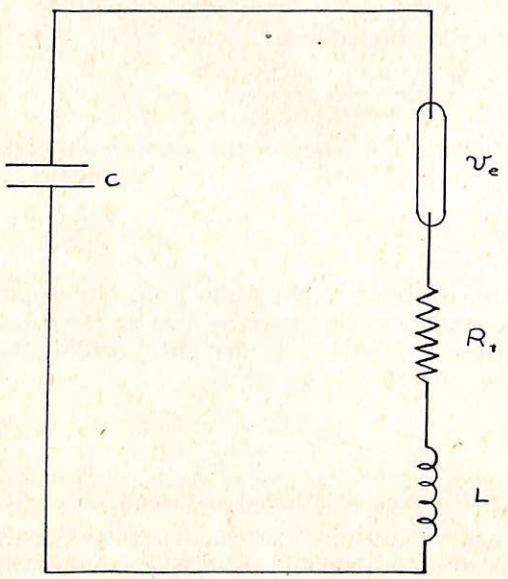


Fig. 15.

Under the conditions expressed by (38) the discharge is oscillatory, and, provided extinction occurs for zero current, the time of discharge is given by $wt = \pi$. At the end of this period the discharge current is zero, lamp extinction occurs, and the condenser voltage is given by

$$v = -\epsilon^{-\pi R_1 t/2Lw}(E - v_e) + v_e \tag{39}$$

In the limiting case of $R_1 = 0$,

$$v = -E + 2v_e \tag{40}$$

From these results it will be noted that the possibility exists of failing to discharge completely the condenser. Hence it is desirable that R_1 should be sufficiently high so that the reversed charge is of negligible magnitude. However, in practice, in spite of keeping L to a low value, the condenser is frequently to have a reversed e.m.f. following a discharge. The discharge time is given by $t = \pi/w$ and, speaking photographically, the effective value of this is generally greater than when inductance is absent, owing to the relatively slow rate at which the current rises from its zero value. Hence, for the photography of high-speed objects, it is most important that L should be as small as possible.

Considering the case when $\left(\frac{R_1^2}{4L^2} - \frac{1}{LC}\right)$ is positive, the solution of (37) is

$$v = A\epsilon^{a_1 t} + B\epsilon^{a_2 t} + v_e$$

where

$$a_1 = -\frac{R_1}{2L} + \sqrt{\frac{R_1^2}{4L^2} - \frac{1}{LC}}$$

$$a_2 = -\frac{R_1}{2L} - \sqrt{\frac{R_1^2}{4L^2} - \frac{1}{LC}}$$

In this case the initial conditions are

$$v = E = A + B + v_e$$

$$\frac{dv}{dt} = 0 = a_1 A + a_2 B$$

from which

$$v = \frac{E - v_e}{a_1 - a_2}(a_1 \epsilon^{a_2 t} - a_2 \epsilon^{a_1 t}) + v_e \tag{41}$$

In this case the condenser takes a theoretically infinite time to discharge, the voltage finally reaching a value v_e. This final value is the same as when inductance is absent, the discharge in this case being governed by (32). However, even under the conditions given by (41), the discharge current takes a finite time to reach its maximum value, whereas in (32) the maximum is reached, theoretically, instantaneously. Hence, again, for high-speed work inductance must be avoided. Further points concerning

the effects of inductance are that, for the same value of R_1, its presence reduces the maximum value of the discharge current and light output. With regard to the first of these effects, in extreme cases the reduction in current may be such as to prevent the glow from developing into an arc.

Triggering Circuits—Single-Flash.

In circuits such as those shown by Figs. 3, (a) and 9, the lamp may be said to be self-triggered, *i.e.* the striking voltage is less than the voltage of the supply, and thus the lamp breaks down upon the condenser voltage reaching the striking value. In the case of single-flash lamps the moment of discharge must, generally, be precisely controlled and, frequently, synchronised with the action of some phenomenon of which a photographic record is desired. Furthermore, it may be necessary to synchronise the phenomenon, the lamp discharge, and the camera shutter. Triggering circuits of single-flash lamps are, generally, of a simpler character than those of the multi-flash type, and hence the former will be treated first.

The simplest form of single-flash circuit for a diode lamp is shown by Fig. 16. On depressing the push button P, the condenser commences to charge in accordance with (13) and, after a theoretically infinite time, acquires a voltage E. However, after

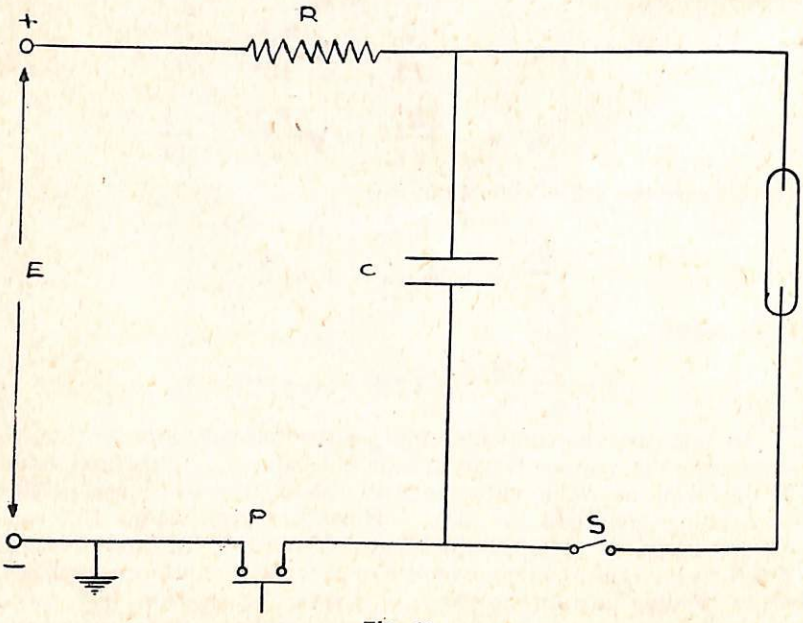


Fig. 16.

a relatively short time the voltage on C rises to within a few per cent. of E and the push-button is then released. A relay operated by the current in R may serve to show (by switching an indicator lamp either on or off) when C is, for all practical purposes, fully charged. Alternatively, an electrostatic voltmeter, connected across C, may be employed. Closure of the high-tension switch S now discharges the condenser through the lamp and thus produces a single flash of light. It is evident that with this circuit the initial voltage on the condenser may be made considerably greater than the normal lamp striking voltage, and a correspondingly brighter flash of light produced. As shown, the switch S is for manual operation and in many instances it is necessary to synchronise closure of this with the camera shutter and, perhaps, the phenomenon under consideration. However, more will be said of this after describing electrical methods of switching the condenser to the lamp.

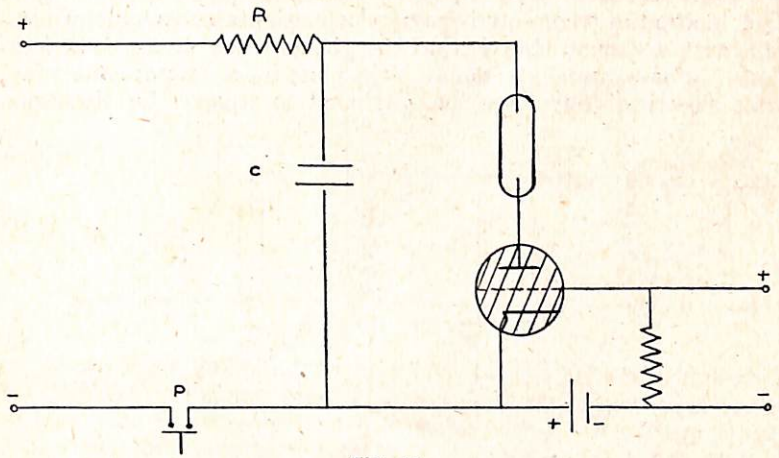


Fig. 17.

The switch of Fig. 16 may be replaced by a thyratron, as shown in Fig. 17. A negative potential is normally applied to the thyratron grid to maintain the anode-cathode circuit in a non-conducting state. If, now, a positive potential of suitable magnitude is applied to the grid, the thyratron will become conducting and the anode circuit resistance will fall to a low value. This, of course, permits the condenser to discharge through the lamp. As the capacitance of the lamp electrodes is, generally, far smaller than that of those of the thyratron, the voltage across the lamp, before conduction occurs is, approximately, equal to that on the condenser until the voltage of the latter reaches the striking voltage. Because of the negatively biassed thyratron, the lamp cannot strike, and hence as the voltage of the condenser continues to rise the voltage in

excess of the lamp striking voltage appears between anode and cathode of the thyratron. Hence, during charging of the condenser, the anode voltage of the thyratron is given by $(v - v_s)$ volts. Finally this voltage becomes $(E - v_s)$ volts, and if K is the value of the thyratron control ratio, the value of the negative grid bias voltage is given by

$$E_g \geq \frac{(E - v_s)}{K}$$

Of course, by varying E_g, the discharge can be made to occur at any voltage between v_s and E.

It is evident that the circuit of Fig. 17 readily lends itself to remote control because relatively low voltages and currents are needed to trigger the lamp. Furthermore, the action is particularly rapid because the ionization time of the thyratron is only a few microseconds after a positive impulse is applied to the grid. This method of triggering is particularly adaptable to synchronisation with a camera shutter and the phenomenon under consideration. For example, a sound picked up by a microphone may, after electrical conversion, be employed to trigger the discharge.

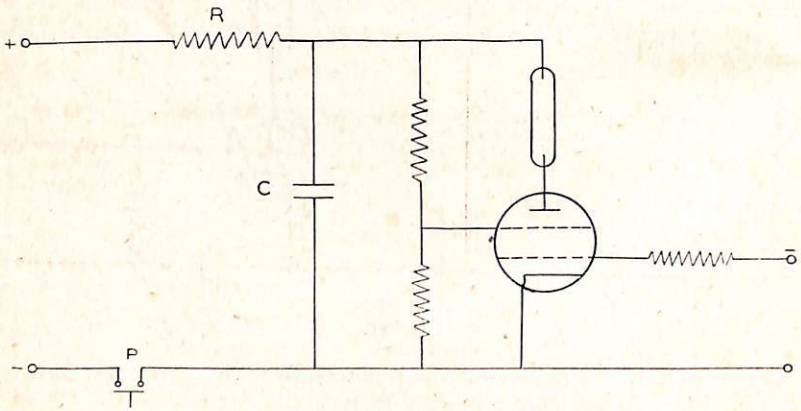


Fig. 18.

As an alternative to a thyratron a Neostron may be employed in the manner shown by Fig. 18. The screen is positively biassed and a negative impulse on the grid triggers the lamp. It is necessary to keep the screen voltage low in order that extinction of the glow between screen and cathode shall occur after triggering. Of course, the lower the screen potential the higher must be the value of the negative impulse to produce a discharge. The maximum permissible anode voltage of a Neostron is 450 volts. Hence the value of the supply voltage must not exceed $(450 + v_s)$ volts.

For triggering a lamp with striking and supply voltages of respectively 170 and 500 volts the author employs a screen voltage of 48 volts and a negative impulse of 72 volts.

Three-Electrode Lamps.

The most commonly employed lamps for single-flash work are those having three electrodes, two internal and one external. As previously explained, the latter electrode usually takes the form of a wire wound round the outside of the lamp. In contrast to two-electrode, single-flash lamps, striking potentials of three-electrode types are very considerably in excess of the condenser voltage. This necessitates a triggering voltage which may be from 3 to 10 times that of the condenser voltage. Thus to trigger a lamp operating from a condenser charged to 2000 volts, a voltage impulse of 10,000 to 15,000 volts may be necessary. The time of the impulse being extremely short, this may be readily obtained from equipment of low power capacity.

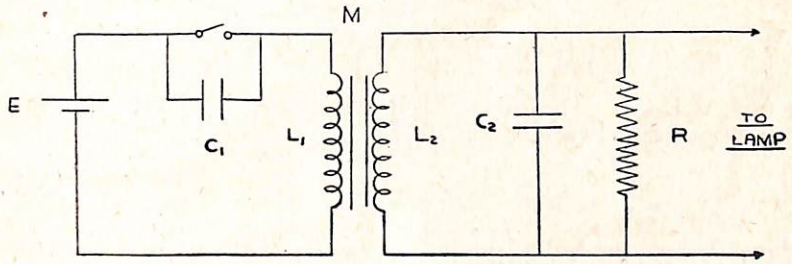


Fig. 19.

A simple method of obtaining a high voltage impulse is indicated by Fig. 19. A small oscillation transformer (induction coil) has the primary winding connected in series with a low voltage supply and a manually-operated switch. The supply need only furnish an ampere or so at a few volts, the function of the condenser being to suppress arcing when the switch is opened. In Fig. 19, C_2 represents the self and associated capacity of the secondary and R the effective resistance of the system. Thus R comprises the losses and any leakage resistance.

Assuming that a current has been produced in the primary by closure of the switch, then on opening the switch the circuit conditions may be expressed by

$$L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} + v_2 = 0 \qquad (42)$$

$$L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} + v_1 = E \qquad (43)$$

where i_1 and i_2 are the instantaneous values of the primary and secondary currents, v_1 and v_2 the instantaneous voltages on the primary and secondary capacitances and E is the applied voltage responsible for I_0, *i.e.* the current at the moment of switch opening. The solution of (42) and (43) may be shown to be*

$$v_2 = \epsilon^{-t/2CR} \frac{I_0}{n\,C\,w} \sin wt \qquad (44)$$

where $C = C_2 + C_1/n^2$, n is the ratio of secondary to primary turns, and $w = 2\pi f = 1/\sqrt{L_2C}$, approximately. The ratio v_2/I_0, *i.e.* the secondary volts per primary ampere, may, with suitable design, reach a very high value, *e.g.* 10,000. Evidently an oscillation transformer is a suitable means of producing the high voltage impulse necessary to trigger the three-electrode type of lamp.

It will be noted from (44) that the discharge is oscillatory. The first maximum occurs, approximately, for $t = \pi/2w$ second.

Hence

$$v_{2\,max.} = \epsilon^{-\frac{\pi}{4R}\sqrt{\frac{L_2}{C}}} I_0 \sqrt{\frac{L_1}{C}}$$

as $n = \sqrt{L_2/L_1}$. The value of R is usually such that the exponential factor lies between 0·5 and 0·75. Thus

$$v_{2\,max.} = AI_0\sqrt{\frac{L_1}{C}} \qquad (45)$$

where A has the value quoted. Typical values are $L_1 = 0{\cdot}01$ henry, $C_1 = 0{\cdot}1\ \mu$ F, $C_2 = 0{\cdot}0001\ \mu$ F and $n = 50$. In this case (45) becomes

$$v_{2\,max.} = 8500\ AI_0$$

A method of operating a three-electrode flash-lamp is now apparent. The supply and transformer switches are closed, whereupon the condenser charges, and a current is built up in the transformer primary winding. Opening the switch of Fig. 19 now produces an impulse which triggers the lamp.

Thyratron Control.

Fig. 20 shows a circuit in which triggering is effected by means of a thyratron. The thyratron is biassed, as shown, and triggering is produced by applying a positive impulse to the grid. When conduction commences, a high voltage is induced in the secondary of T and this triggers the lamp. If the influence of the secondary winding is neglected, then, on breakdown of the thyratron, a voltage equal to $(E - e)$ is momentarily applied to the primary of T. Hence the approximate value of the triggering

* "Aircraft Electrical Engineering," F. G. Spreadbury (Pitman), p. 13.

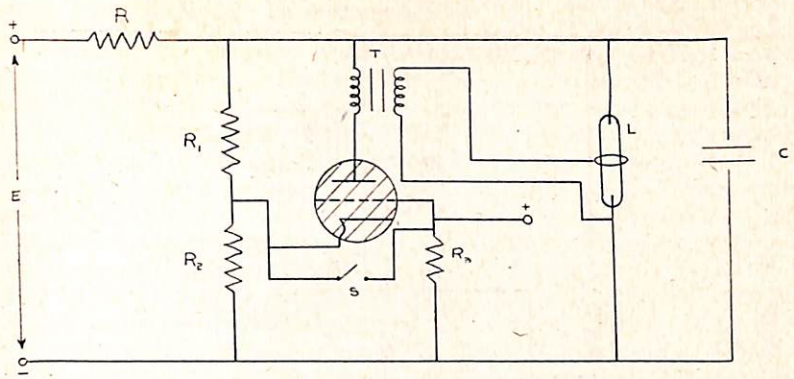


Fig. 20.

voltage is n (E – e) volts, where e is the anode voltage of the thyratron after breakdown, about 15 to 20 volts. Thus

$$v_{2\,\max.} = nE \text{ approximately.}$$

where n is the transformer turns ratio. With this method of triggering the lamp discharge occurs particularly rapidly after the positive impulse is applied. This is because the time between the application of the impulse and the appearance of $v_{2\,\max.}$ at the lamp electrodes is approximately equal to the ionization time of the thyratron.

In Fig. 20 R_2 serves a further purpose beyond providing the bias for the valve, this being to ensure that the condenser discharges mainly through the lamp rather than through the thyratron. It will be noted that the valve anode and grid supplies are obtained from the same source as that of the lamp. However, they may, if desired, be obtained from a separate lower voltage source.

If it is desired to trigger the lamp manually, the switch S is closed. This removes the potential difference between grid and cathode and thus destroys the bias.

Neostron Control.

As an alternative to the thyratron of Fig. 20, a Neostron may be employed in the manner shown by Fig. 21. In this case a negative impulse applied to the grid causes the anode-cathode voltage to fall to a low value, thus suddenly causing a voltage equal to (E – e) volts to appear across the primary of the transformer. The function of R_4 is similar to the secondary function of R_2 in Fig. 20.

A further method of obtaining a high-voltage impulse is shown by Fig. 22, (a). The condenser is charged through the resistance R and then discharged through the transformer primary and thyratron on application of a positive impulse to the grid. If

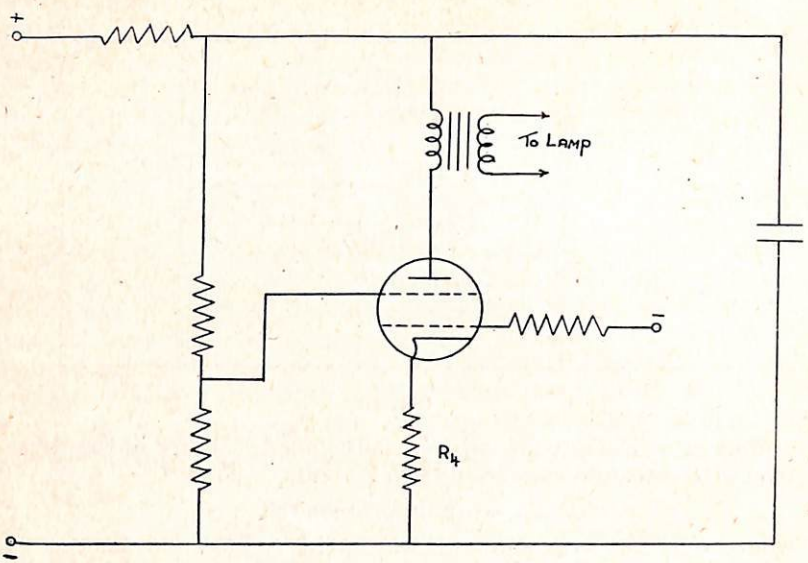


Fig. 21.

the influence of the transformer secondary winding be neglected, the primary circuit conditions are those already treated on page 30, the instantaneous value of the condenser voltage being given by (38). The approximate values of the primary and secondary voltages are given by

$$v_1 = \epsilon^{-R_1 t/2L} (E - v_e) \left(\frac{R}{2 L w} \sin wt + \cos wt \right)$$

and $v_2 = n v_1$

Hence the maximum value of v_2 is $n (E - v_e)$. As an alternative to (a), a Neostron may be employed as at (b).

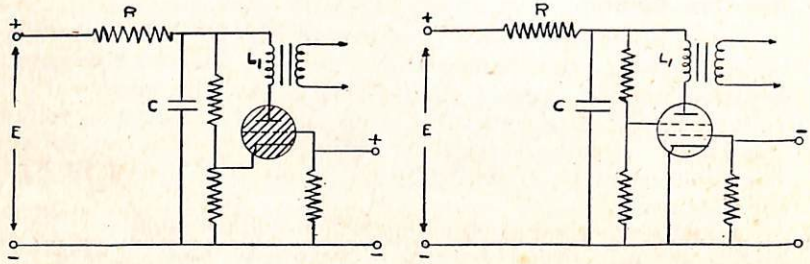


Fig. 22.

Multi-Flash Circuits. Stroboscopes.

Probably the simplest multi-flash circuit is that of Fig. 3 (a). As stated previously, this circuit is self-excited (or self-triggered) and from this arises its simplicity. The flashing frequency is given by (16) and is varied by varying R. A fixed resistance is connected in series with R to avoid inadvertently placing the lamp directly across the source of supply. As shown on page 25, there is a minimum value for R and below this value oscillations cease. Because of the low extinction current of lamps of the Osglim type, these are generally unsuitable for use in the circuit of Fig. 3 (a). Thus if the extinction current is 0·5 Ma., then with a supply voltage of 250 volts, the minimum value of R is 0·25 megohm. With this value, to obtain frequencies usually required in practice, C must be so small that, coupled with the high extinction voltage, the illumination intensity is quite inadequate. However, a Neostron tube will give very satisfactory results employed in either circuit (a) or (b).

A disadvantage of circuit (a) is that a variation in supply voltage causes a variation in frequency. This, of course, is indicated by (16). Furthermore variations in v_s and v_e also have a similar effect.

Differentiating f with respect to E,

$$\frac{df}{dE} = \frac{v_s}{RCE\ (E - v_s)\ \log_\epsilon^2 E/(E - v_s)}$$

if v_e is small compared with v_s.

Also,

$$\frac{f}{E} = \frac{1}{RCE\ \log_\epsilon E/(E - v_s)}$$

and

$$\frac{df}{f} \Big/ \frac{d\,E}{E} = \frac{1}{(E/v_s - 1)\ \log_\epsilon\ [\ (E/v_s)/(E/v_s - 1)\ ]} \qquad (46)$$

which gives the ratio of the fractional change in frequency consequent on a fractional change in voltage. It will be noted that (46) is a function of E/v_s. Reference to Fig. 23 shows that (46) is a decreasing function of E/v_s and hence for frequency stability E/v_s should be high. However, as indicated by (20), the electrical efficiency is inversely proportional to this quantity and hence frequency stability can only be secured at the expense of low efficiency. An alternative to making E/v_s high is, of course, to employ a stabilised voltage supply.

Apart from possible variations in E, v_s is also liable to sudden fluctuations as well as to a progressive change during the life of the

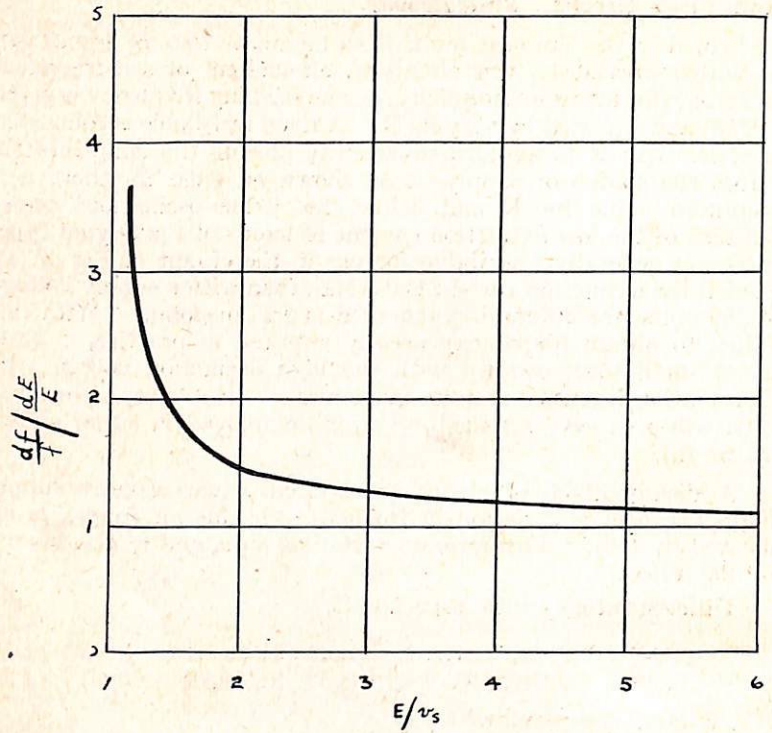


Fig. 23.

lamp. Also v_s varies with different lamps. All these factors, of course, militate against the use of the circuit of Fig. 3 (a) for speed measurement. Hence this circuit, when employed at all, finds its principal application to stroboscopic work.

External Triggering Circuits.

Because of the limitations of circuit (a), Fig. 3, this is generally employed for stroboscopic work only, *i.e.* the arrest of motion and the production of slow motion effects. For precise speed measurement, as well as stroboscopic work, it is customary with Neostrons to employ circuit (b) in which the lamp is periodically triggered from some external source. In this case the potential of the screen is made lower than in circuit (a) so that, in the absence of a triggering impulse on the grid, oscillation does not occur. If, now, a negative voltage of suitable amplitude is periodically impressed on the grid, the lamp will flash each time this voltage is applied. Evidently if the negative impulse frequency is accurately known and can be continuously varied, precise speed measurements may be made of

rotating bodies and the oscillation frequency determined of reciprocating ones.

A method of applying the negative impulses is by means of a motor-driven contact maker. Thus if the contacts are briefly closed once per revolution, the lamp will give one flash for each revolution. Hence, if an electrical tachometer is coupled to the motor, and the speed of the latter can be varied, the flashing frequency will be determined.

A characteristic of most external triggering circuits is that they cause the discharge voltage of the condenser to become progressively lower as the flashing frequency is increased. This, of course, is in contrast to the previously described circuits, where the discharge voltage is independent of frequency. The condenser potential is given by (14) and from this it is evident that as t is reduced v becomes smaller. Hence, with external triggering, the amount of light per flash is a decreasing function of the flashing frequency. This effect can, to some extent, be reduced by arranging the constants of the charging circuit to be such that, at low frequencies, the condenser is practically charged to E before the triggering pulse arrives. Then, as the frequency of the pulse increases, the initial reduction in v will be relatively small. However, in practice, the reduction in light per flash is of small importance because the *average* value of the integrated light output increases with the flashing frequency. Further details will be given concerning this in dealing with stroboscope design.

Electronic Triggering.

Instead of periodically triggering a stroboscope by mechanical switching, it is usual to use some electronic method. For example, it is possible to employ a variable-frequency, sinusoidal valve oscillator and feed the output of this to the grid of the Neostron. Then, provided the output voltage has sufficient amplitude, triggering will occur at some point of a negative half cycle. In order to obtain satisfactory results, the amplitude of the triggering voltage should be such that there is only one cycle of this to one cycle of the condenser charging voltage. (See Fig. 24). Having secured this condition, the flashing frequency of the lamp will then be equal to the oscillator frequency. The oscillator can, of course, be calibrated in frequency or r.p.m. by virtue of the position of the oscillator tuning element.

It has been indicated that the amplitude of the triggering voltage of a sinusoidal oscillator, employed in the present connection, is of some significance. Hence, before proceeding to discuss special types of oscillators usually employed with stroboscopes, some attention will be directed to this.

With the oscillator operating at constant frequency, variation of the amplitude of the triggering impulse has some interesting

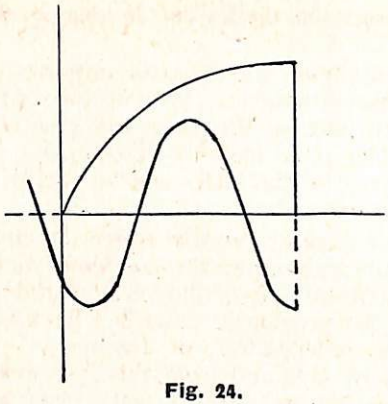


Fig. 24.

effects on the flashing frequency. With the lamp flashing regularly it is evident that the periodic time as given by (15) must be a multiple of the periodic time of the triggering voltage. Thus $t_1 = nt_2$ where t_2 is the periodic time of the triggering voltage and n is an integer. Let v be the potential difference between the screen and grid to cause striking. Then

$$v = v_{ss} + v_{sg}$$

where v_{ss} and v_{sg} are respectively the screen and grid voltages at striking. The instantaneous value of the screen voltage is, of course, given by

$$v_s = \frac{R_2}{R_1 + R_2} [E - (E - v_e)\ \epsilon^{-t/CR}] \qquad (47)$$

Suppose that $n = 4$. Then $t_1 = 4t_2$ and substitution of this value in (47) gives v_{ss}. The value of v_g to cause striking is now obtained from $(v - v_{ss})$ and, assuming a sinusoidal waveform for the triggering voltage, the amplitude of the latter cannot be smaller than the value of v_g so obtained. These conditions are shown by Fig. 25, where v_e is taken as zero. If, now, the amplitude of the triggering voltage is slowly increased, breakdown will occur at an earlier part of the wave, and the points P_1, P_3 will move to the right; *i.e.* a phase displacement between the two waves will occur. As the

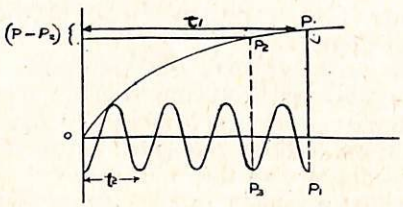


Fig. 25.

amplitude is continually increased, the potential difference P_2P_3 increases until $P_2\ P_3 = PP_1$. At this point triggering will tend to take place at P_3 rather than at P_1 and irregular flashing will occur. The irregularity at this point is due to t_1 no longer being a multiple of t_2. As the amplitude is still increased a value will be reached at which $P_2\ P_3 = PP_1$ with $t_1 = 3t_2$, and, at this point, flashing will be regular. The necessary increase in amplitude over that corresponding to PP_1 is, of course, $(P - P_2)$. It is evident that, ultimately, there will be only one cycle of the triggering voltage to that of the condenser charging voltage and, as stated previously, the amplitude of the former voltage should be such as to effect this. Although the flashing frequency may be varied by varying the amplitude of the triggering voltage, it will be appreciated that the variation is discontinuous and, is, therefore, unsuitable for stroboscopic work. Furthermore, the periodic time of the flash can be a multiple of t_2 only, and the flashing frequency a sub-multiple of that of the triggering voltage.

Triggering by Pulse Generators.

Referring to Fig. 24, where the lamp is triggered by a sinusoidal grid voltage, let it be assumed that variations in v_s are likely to occur. Thus if v_s increases, striking will occur at a later point in the triggering cycle with a consequent momentary modification to the flashing frequency. It is apparent that if v_s is subject to uncontrolled variations, unsteady impressions are likely to be received of objects undergoing observation. As stated previously, for various reasons v_s is likely to vary from time to time, and to avoid the possible detrimental consequence of this, it is preferable to trigger the lamp by means of a pulse generator, such as a multivibrator or blocking oscillator. In this case the base line of Fig. 24 is intersected practically at right-angles, and, provided the pulse is of adequate amplitude, the lamp is triggered at precisely equal time intervals, resulting in a remarkably steady impression of a viewed object. The stroboscope of Fig. 32, designed and constructed by the author, employs a Neostron triggered by a multivibrator oscillator. This oscillator, to be shortly described, is particularly suitable for triggering purposes as the output voltage possesses a particularly steep wavefront.

The Multivibrator Oscillator.

This oscillator consists of two valves coupled in the manner shown by Fig. 26.* When each valve and its associated components is a replica of the other, the oscillator is said to be "symmetrical." This form of multivibrator will be considered first. The method of operation is as follows. Let it be assumed that the

* Alternatively a double triode, such as the Mullard ECC 32, may be employed.

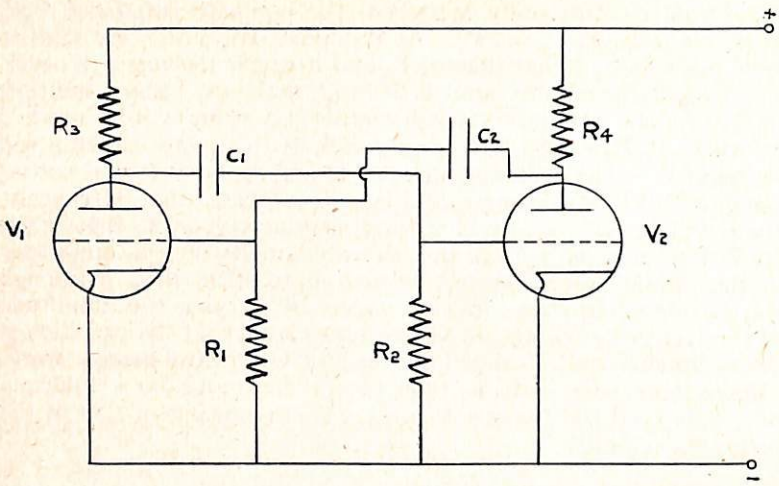


Fig. 26.

anode current in V_1 is increasing. Then the potential of this anode is falling and C_1 is discharging through V_1 and R_2. This causes the grid of V_2 to become negative, thus decreasing the anode current of this valve. The potential of the anode of V_2 thus rises causing C_2 to charge. The charging current of C_2 passes through R_4 and the cathode-grid circuit of V_1, this causing the grid of the latter to become positive. The effect of this is to increase further the anode current of V_1 which will, in the manner already described, further decrease the anode current of V_2. It is evident that the process is rapidly cumulative and will proceed until the negative potential of the grid of V_2 is such that the anode current of this valve is completely cut off. Actually, as will be shown, the magnitude of the negative grid potential of V_2 becomes much larger than that needed just to cut off the anode current. The cut-off condition remains until the discharge of C_1 is such that the grid potential of V_2 rises to that value just sufficient to produce cut-off. At this point current recommences to flow in V_2, the cumulative effect again occurs, but this time it is V_1 which is cut off. Evidently, this process may continue indefinitely, *i.e.* continuous oscillations are produced. The voltage impulses across either R_1 or R_2 are employed for triggering the stroboscope lamp, and it is now necessary to determine the frequency and amplitude of these impulses.

As soon as V_2 is cut off, C_2 commences to charge through R_4 and the *internal* resistance of the cathode-grid circuit of V_1 (not the *slope* resistance). Provided the latter is small compared with that of R_4, and R_4 is small compared with R_1 and R_2, the charging

time of C_2 is small compared with the discharge time of C_1. Hence during the greater part of the time V_2 is cut off, the potential difference across C_2 is equal to that of the H.T. supply, E. When V_1 is cut off, the same argument applies to C_1. Assuming V_1 to be cut off, at the moment conduction is re-established, the potential of the anode (relative to the cathode) falls almost instantaneously (due to the rapid cumulative action) from E to some lower value v_1. As the potential of C_1 cannot change instantaneously, there is an almost instantaneous change in potential difference across R_2 from zero to $(E - v_1)$ volts. This follows because, if C_1 is charged to E volts at the moment of changeover, there is initially no potential difference between grid and cathode of V_2 and hence across R_2. V_1 will now conduct while the voltage R_2 changes from $(E - v_1)$ to v_c, where v_c is the normal cut-off voltage of V_2. Hence the amplitude of the negative impulse on R_2 is $(E - v_1)$ volts.

In order to find the cut-off period of V_2, it will be assumed that v_1 is constant, which, actually, is the case for the major part of the period, provided $R_2 > R_4$. Then

$$v_1 = v' + i R_2 \tag{48}$$

where v' and i are respectively the voltage and current of C_1.

Differentiating (48),

$$\frac{dv'}{dt} + R_2 \frac{di}{dt} = 0$$

or

$$i + C_1 R_2 \frac{di}{dt} = 0$$

Integrating

$$\log_\epsilon \frac{i}{K} = - \frac{t}{C_1 R_2}$$

where K is a constant. When $t = 0$, $i = i_0$. Hence $K = i_0$ and

$$t = C_1 R_2 \log_\epsilon \frac{i_0}{i}$$

$$= C_1 R_2 \log_\epsilon \frac{R_2 i_0}{R_2 i}$$

$$= C_1 R_2 \log_\epsilon \frac{E - v_1}{v_c} \tag{49}$$

As the multivibrator under consideration is assumed to be symmetrical, the periodic time is twice that given by (49), *i.e.*,

$$2 C_1 R_2 \log_\epsilon \frac{E - v_1}{v_c} \tag{50}$$

The oscillation frequency is, of course,

$$f = \frac{1}{2\,C_1\,R_2\,\log_\epsilon \dfrac{E - v_1}{v_c}} \qquad (51)$$

In deriving the foregoing results it has been assumed that v_1 is constant and equal to the value which the anode voltage has during the major part of the conducting cycle. This value is equal to that of the anode voltage when the voltage drop on R_1 is zero, *i.e.* when the grid of V_1 is unbiassed. This value can, of course, be readily obtained by measurement under static conditions, *i.e.*, with C_2 and C_1 disconnected so that no oscillatory action occurs. The initial value of v_1 at the moment of changeover is somewhat lower than the static value because at this moment the potential of the grid of V_1 has a small positive value. Hence, although the results given by (49), (50) and (51) are approximately correct, the amplitude of the negative impulse, *i.e.* $(E - v_1)$, is underestimated if the static value for v_1 is employed. The initial value of v_1 cannot be readily determined and hence must be found by experiment.

When a multivibrator is not symmetrical the periods of the two parts of a cycle will be different, one part being given by

$$t_1 = C_1\,R_2\,\log_\epsilon \frac{E - v_1}{v_{c2}}$$

and the other by

$$t_2 = C_2\,R_1 \log \frac{E - v_2}{v_{c1}}$$

The complete period is, of course, $T = t_1 + t_2$.

Frequency Variation.

For stroboscopic work it is necessary to vary the frequency of the oscillator. This may be effected in either one of two ways. Referring to (51), an obvious method of frequency variation is by variation of the product $C_1\,R_2$. However, both $C_1\,R_2$ and $C_2\,R_1$ must be simultaneously variable. This may be achieved by means of ganged rotary resistances and banks of condensers, the latter being varied by means of coupled switches.

A simple method of frequency variation, and that employed in the stroboscope of Fig. 32, consists of applying a variable positive bias to the grids of the valves in the manner indicated by Fig. 27. Considering the signs of the various potentials acting in the circuit C_1, V_1, v_b, R_2, we see that the initial value of the voltage on R_2 as V_1 starts to conduct is $E - v_1 + v_b$. The potential difference, however, between the grid and cathode of V_2 is $[(E - v_1 + v_b) - v_b]$ $= (E - v_1)$. As before, conduction through V_2 recommences when

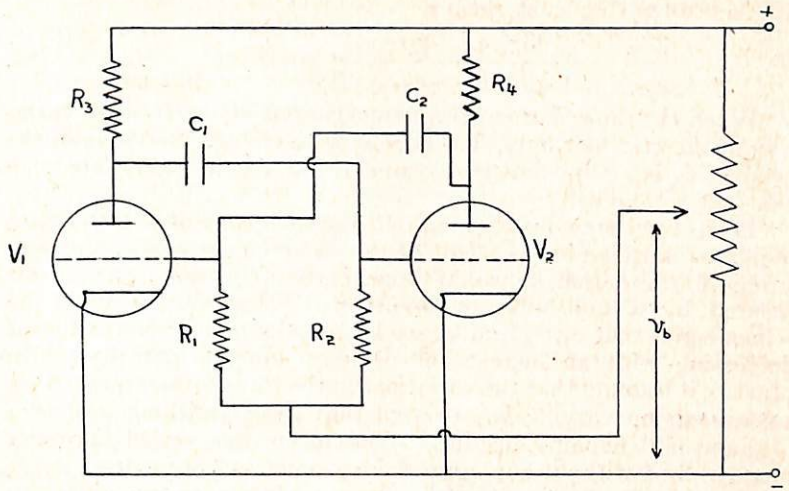


Fig. 27.

the cathode-grid potential difference is equal to v_c, *i.e.* when the voltage on R_2 is $(v_c + v_b)$. Hence the periodic time is now

$$t = 2\,C_1\,R_2 \log_\epsilon \frac{E - v_1 + v_b}{v_c + v_b} \qquad (52)$$

the voltage variation on R_2 during the discharge of C_1 being $[\,(E - v_1 + v_b) - (v_c + v_b)\,] = (E - v_1 - v_c)$. Thus the voltage variation on R_2 is independent of the value of the bias and the amplitude of the oscillations is independent of frequency. For given values of C_1 and R_2 the frequency is a maximum when the logarithmic term of (52) is a minimum, *i.e.* when $(E - v_1 + v_b)\,/\,(v_c + v_b)$ is a minimum. Differentiating and equating to zero, we find that t is a minimum when $v_b = E - v_c$ or, approximately, $v_b = E$, as v_c is small compared with E. Hence the minimum period and maximum frequency are respectively given by

$$t_{\text{min.}} = 2\,C_1\,R_2 \log_\epsilon \frac{2\,E - v_1 - v_c}{E}$$

$$f_{\text{max.}} = \frac{1}{2\,C_1\,R_2 \log_\epsilon \dfrac{2\,E - v_1 - v_c}{E}}$$

The minimum frequency is given by

$$f_{\text{min.}} = \frac{1}{2\,C_1\,R_2 \log_\epsilon \dfrac{E - v_1}{v_c}}$$

and hence the frequency ratio is

$$\frac{f_{max.}}{f_{min.}} = \frac{\log_\epsilon (E - v_1) / v_c}{\log_\epsilon (2E - v_1 - v_c) / E} \qquad (53)$$

When the desired frequency range cannot be covered by variation of the grid bias only, it is necessary to change the value of the product $C_1 R_2$. For the stroboscope of Fig. 32 the values are such that (53) is about 6.

It has been previously stated that the frequency of a stroboscope oscillator must be independent of the value of the supply voltage. From (51) and (52) it would appear that this condition is not secured by a multivibrator oscillator. However, it must be remembered that v_1, v_b and v_c are all functions of E, increasing or decreasing with an increase or decrease in this quantity. In practice it is found that the variations in the three former quantities, consequent on varying E, are such that the logarithmic terms in (51) and (52) remain constant. The author has varied E over a range of 2 : 1 without any appreciable change in t occurring.

Some oscillograms of multivibrator performance are given by Figs. 35 to 42 and will be explained in conjunction with the stroboscope of Fig. 32.

The Blocking Oscillator.

This impulse generator is shown by Fig. 28 and generates high voltage, short-lived pulses, the frequency of which may be easily

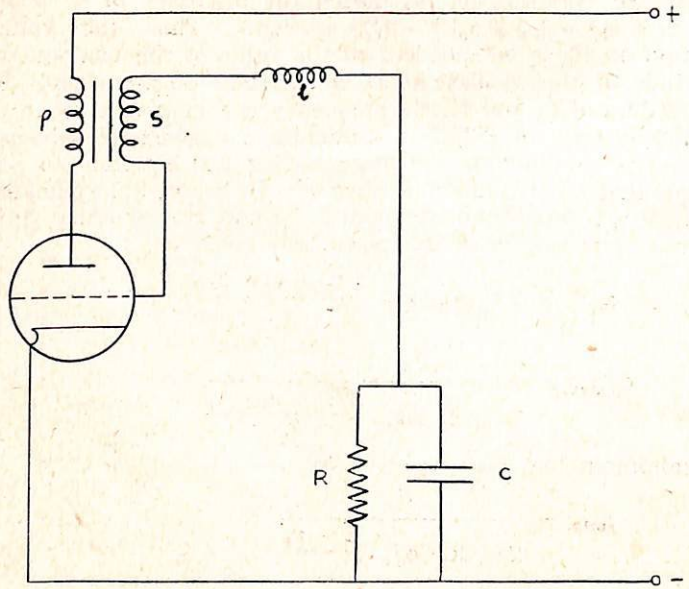


Fig. 28.

varied by means of variation of R or C. In order to appreciate the method of operation of the oscillator, assume that the voltage (and current) of the transformer primary tends to increase, and that the transformer connections are such that, as a result of this increase, the grid end of the secondary becomes positive. The immediate effect of this is a fall in the valve resistance and, owing to its inductance, a further voltage increase across the primary. In practice, this process is rapidly cumulative and results in an almost instantaneous voltage impulse across the primary, the maximum value of which is approximately equal to that of the H.T. supply. An effect of the grid becoming positive is to cause grid current to flow, this current charging the condenser C. Provided the value of C is not too large, nor that of R too small, the voltages across P and S are roughly constant during charging of the condenser.

In order to determine the charging conditions, let l represent the total leakage inductance of the transformer and R_g the cathode grid resistance of the valve over the approximately linear portion of its characteristic. Then, during charging, the conditions may be expressed by

$$L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} = E - E_a \tag{54}$$

$$L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} + l \frac{di_2}{dt} + R_g i_2 + v_2 = 0 \tag{55}$$

where L_1 is the transformer primary inductance, L_2 that of the secondary, M the mutual inductance between the windings, i_1 the primary current, E_a the anode-cathode drop, and i_2 and v_2 are, respectively, the secondary current and condenser voltage.

From (54)

$$\frac{di_1}{dt} = \frac{E - E_a}{L_1} - \frac{M}{L_1} \frac{di_2}{dt}$$

Substituting in (55)

$$L_2 \frac{di_2}{dt} + \frac{M}{L_1}(E - E_a) - \frac{M^2}{L_1} \frac{di_2}{dt} + l \frac{di_2}{dt} + R_g i_2 + v_2 - 0$$

or $$l \frac{di_2}{dt} + R_g i_2 + v_2 = - n (E - E_a)$$

as $M^2 = L_1 L_2$ and $M/L_1 = n$, the transformer transformation ratio.

Writing

$$i_2 = C \frac{dv_2}{dt} + \frac{v_2}{R}$$

we have

$$\frac{d^2v_2}{dt^2} + \left(\frac{1}{CR} + \frac{R_g}{l}\right)\frac{dv_2}{dt} + \left(\frac{R_g}{lCR} + \frac{1}{lC}\right)v_2 = \frac{-n\ (E - E_a)}{lC} \qquad (56)$$

Solving

$$v_2 = A\,\epsilon^{a_1 t} + B\epsilon^{a_2 t} - n\,R\ (E - E_a)\ /\ (R_g + R)$$

where A and B are constants and

$$a_1 = -\frac{b}{2} + \sqrt{\frac{b^2}{4} - c}$$

$$a_2 = -\frac{b}{2} - \sqrt{\frac{b^2}{4} - c}$$

b and c being respectively the coefficients of the terms in dv_2/dt and v_2 in (56). For stroboscopic work the circuit constants are invariably such that the condenser is charged aperiodically. To determine A and B we have the following conditions.

When $t=0$, $v_2=v_c$, $Cdv_2/dt=v_c/R$, where v_c is the value of the negative bias voltage necessary to cut off the anode current under static conditions. If v_c is small, as it normally is, we may take $t=0$, $v_2=0$, $Cdv_2/dt=0$, and

$$v_2 = \frac{n\,R\ (E - E_a)}{R_g + R}\left[\frac{a_1}{a_1 - a_2}\epsilon^{a_2 t} - \frac{a_2}{a_1 - a_2}\epsilon^{a_1 t} - 1\right] \qquad (57)$$

$$i_2 = \frac{a_1\,a_2\,CnR\ (E - E_a)}{(a_1 - a_2)\ (R_g + R)}\ (\epsilon^{a_2 t} - \epsilon^{a_1 t}) + \frac{n\ (E - E_a)}{R_g + R}\left[\frac{a_1}{a_1 - a_2}\epsilon^{a_2 t} - \frac{a_2}{a_1 - a_2}\epsilon^{a_1 t} - 1\right] \qquad (58)$$

From (54)

$$L_1\frac{di_1}{dt} + M\,\frac{a_1\,a_2\,CnR\ (E - E_a)}{(a_1 - a_2)\ (R_g + R)}\ (a_2\,\epsilon^{a_2 t} - a_1\,\epsilon^{a_1 t}) + \frac{a_1\,a_2\,Mn\ (E - E_a)}{(R_g + R)\ (a_1 - a_2)}\ (\epsilon^{a_2 t} - \epsilon^{a_1 t}) = E - E_a$$

and

$$\int di_1 = \frac{E - E_a}{L_1}\int dt - \frac{M}{L_1}\,\frac{a_1\,a_2\,CnR\ (E - E_a)}{(a_1 - a_2)\ (R_g + R)}\int (a_2\,\epsilon^{a_2 t} - a_1\,\epsilon^{a_1 t})\,dt$$

$$- \frac{a_1 a_2 Mn (E - E_a)}{L_1 (R_g + R) (a_1 - a_2)} \int (\epsilon^{a_2 t} - \epsilon^{a_1 t}) \, dt$$

Hence
$$i_1 = \left(\frac{E - E_a}{L_1}\right) t - \frac{M}{L_1} \frac{a_1 a_2 CnR (E - E_a)}{(a_1 - a_2) (R_g + R)} (\epsilon^{a_2 t} - \epsilon^{a_1 t})$$
$$- \frac{Mn (E - E_a)}{L_1 (R_g + R) (a_1 - a_2)} (a_1 \epsilon^{a_2 t} - a_2 \epsilon^{a_1 t}) + K$$

where K is a constant. From the initial condition $i_1 = 0$ when $t = 0$,

$$K = \frac{Mn (E - E_a)}{L_1 (R_g + R)}$$

and
$$i_1 = \left(\frac{E - E_a}{L_1}\right) t - ni_2 \qquad (59)$$

If the circuit constants are suitably chosen (57) indicates that the condenser voltage rapidly rises as though approaching a value of $-nR(E - E_a) / (R_g + R)$ volts. Also (58) indicates that the charging current rapidly rises to a maximum and then falls away relatively slowly. As the condenser voltage approaches $-nR (E - E_a) / (R_g + R)$ the magnitude of the positive grid potential declines with the consequence that the internal resistance of the valve commences to rise. This has the effect of increasing the anode voltage, thus decreasing those of the transformer and, because the upper plate of the condenser now has a negative potential of approximately $-nR(E - E_a) / (R_g + R)$ volts, the anode and grid currents are abruptly cut off. This last condition remains until the voltage on the condenser has fallen to v_c volts. At this point the valve again becomes conducting and the cycle of events is indefinitely repeated. If the assumption is made that the charging time is negligible compared with the discharge time, the periodic time of the oscillation is approximately that necessary for the condenser to discharge from a voltage $-nR (E - E_a)/(R_g + R)$ to v_c volts.

Hence, from (49)

$$t = CR \log_\epsilon \frac{nR (E - E_a) / (R_g + R)}{v_c} \qquad (60)$$

$$f = \frac{1}{CR \log_\epsilon \dfrac{nR (E - E_a) / (R_g + R)}{v_c}} \qquad (61)$$

These results show that the oscillation frequency may not only be varied by varying CR, but also by varying n. As a first approximation the numerator of the logarithmic term may be replaced by nE.

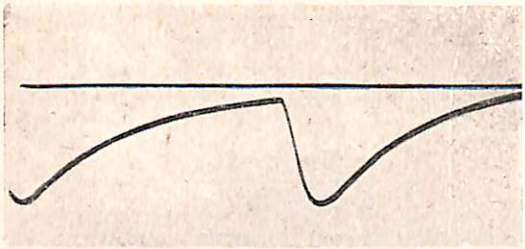


Fig. 29.

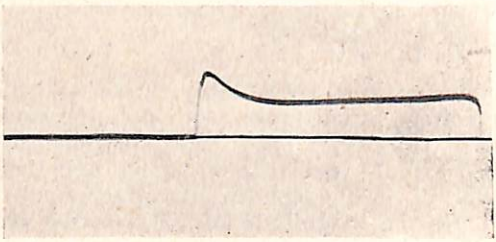


Fig. 30.

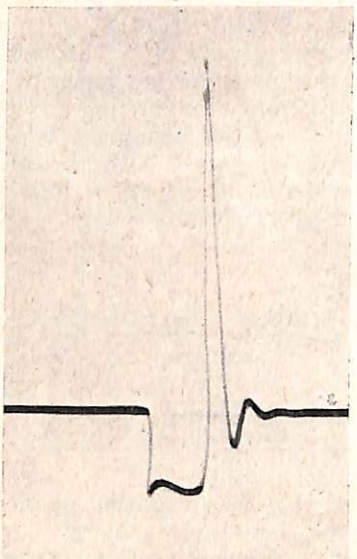


Fig. 31.

Conditions at Cut-Off.

At cut-off there is, generally, a far larger voltage impulse produced across the transformer windings than at the moment the valve becomes reconducting. In the latter case the value of this impulse is, approximately, E volts in the primary winding and nE volts in the secondary winding. For triggering purposes in stroboscopes it is the former impulse which is employed, *i.e.* the impulse at cut-off. In this case the value of the impulse voltage is given by (44) for the secondary winding or by

$$v_1 = \epsilon^{-t/2CR} \frac{I_0}{n^2 Cw} \sin wt \qquad (62)$$

for the primary winding. In (62) C and R represent the same quantities as in (44) and I_0 is the value of the primary current at cut-off, given by the first term of the right-hand member of (59) when t is equal to the charging period. Only this term is taken because only this component of the primary current produces energy storage, it being assumed that the effect of l, in this connection, is negligible.

Similarly to the multivibrator oscillator, variation of the supply voltage has little effect on the blocking oscillator frequency. This is because both numerator and denominator of the logarithmic term in (61) are affected by a change in E. Thus the author has varied E over a range of 2 : 1 without any appreciable change in f occurring.

Reference to Figs. 29, 30, and 31 shows oscillograms of operating conditions in a blocking oscillator. The valve concerned is a Mullard 354V, operated from an anode supply of 23 volts. The transformer has a ratio of unity, the values of R and C being, respectively, 50,000 ohms and 0·1 μF. Fig. 29 shows the condenser voltage. The relatively short charging time will be noted, also the slow discharge from the maximum value to the cut-off voltage. The oscillogram of Fig. 30 gives the anode, *i.e.* primary, current. The exponential character of the early part of the wave is evident while the rising character of the later part shows the influence of the term $(E - E_a)t/L_1$. Fig. 31 shows the voltage across the transformer primary winding. The approximately constant voltage during charging of the condenser is evident, also the swift change to an oscillatory transient at cut-off. It will be observed that the amplitude of the latter is about five times that of the anode supply voltage. It is, of course, this high-voltage transient which may be effectively employed for triggering a Neostron.

Stroboscope Design.

As an example of stroboscope design and construction, Figs. 32, 33, and 34 will be considered which concern an instrument, designed by the author capable of measuring speeds from 500

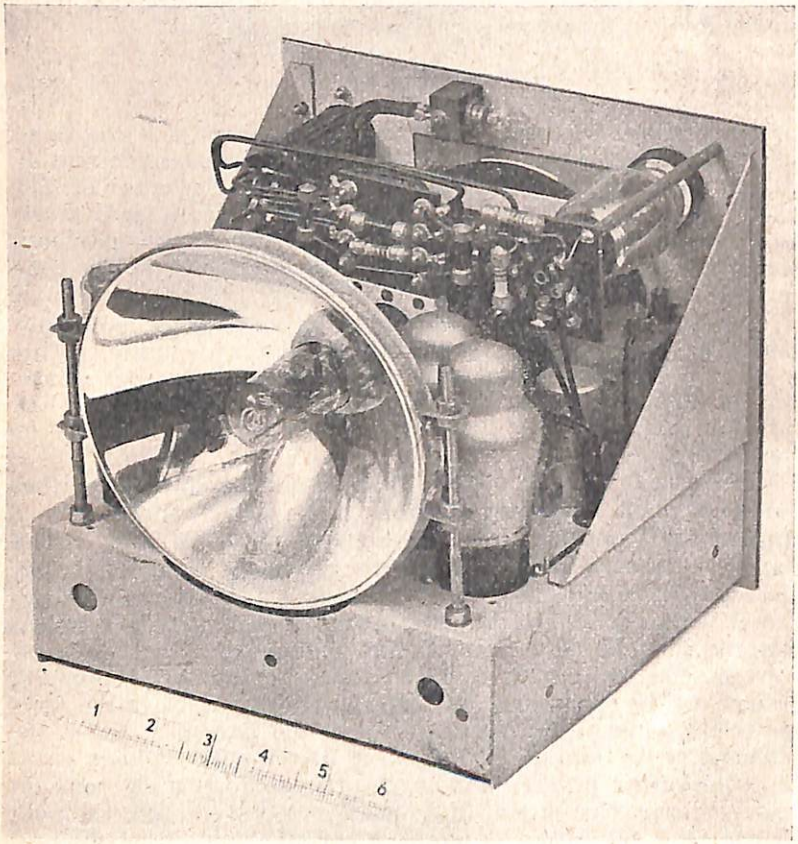


Fig. 32.

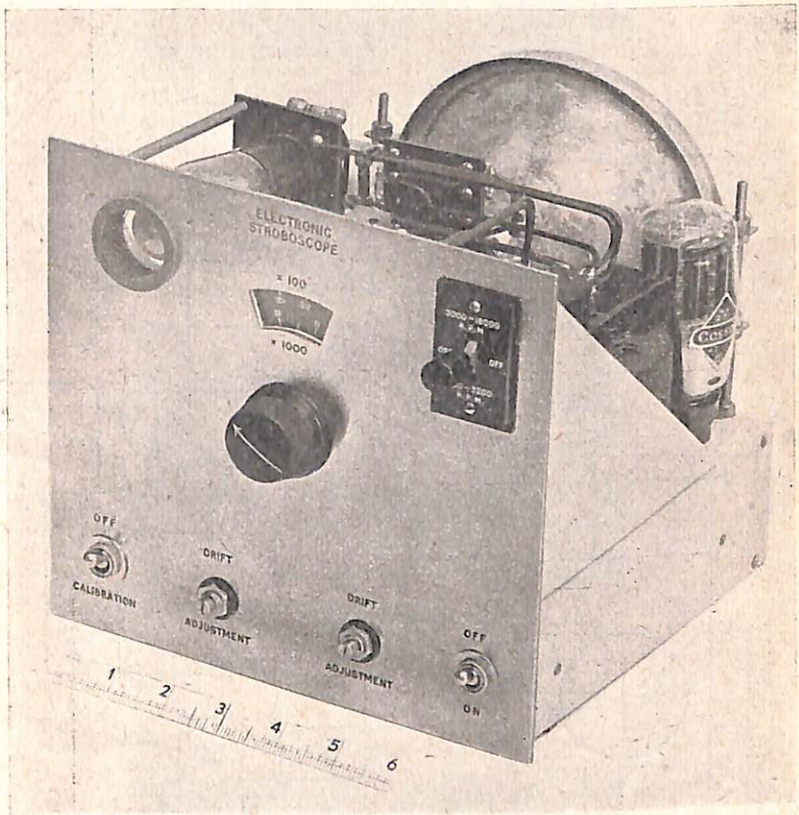

ELECTRONIC
STROBOSCOPE
x 100
x 1000
OFF
CALIBRATION
DRIFT
ADJUSTMENT
DRIFT
ADJUSTMENT
OFF
ON
1
2
3
4
5
6

Fig. 33.

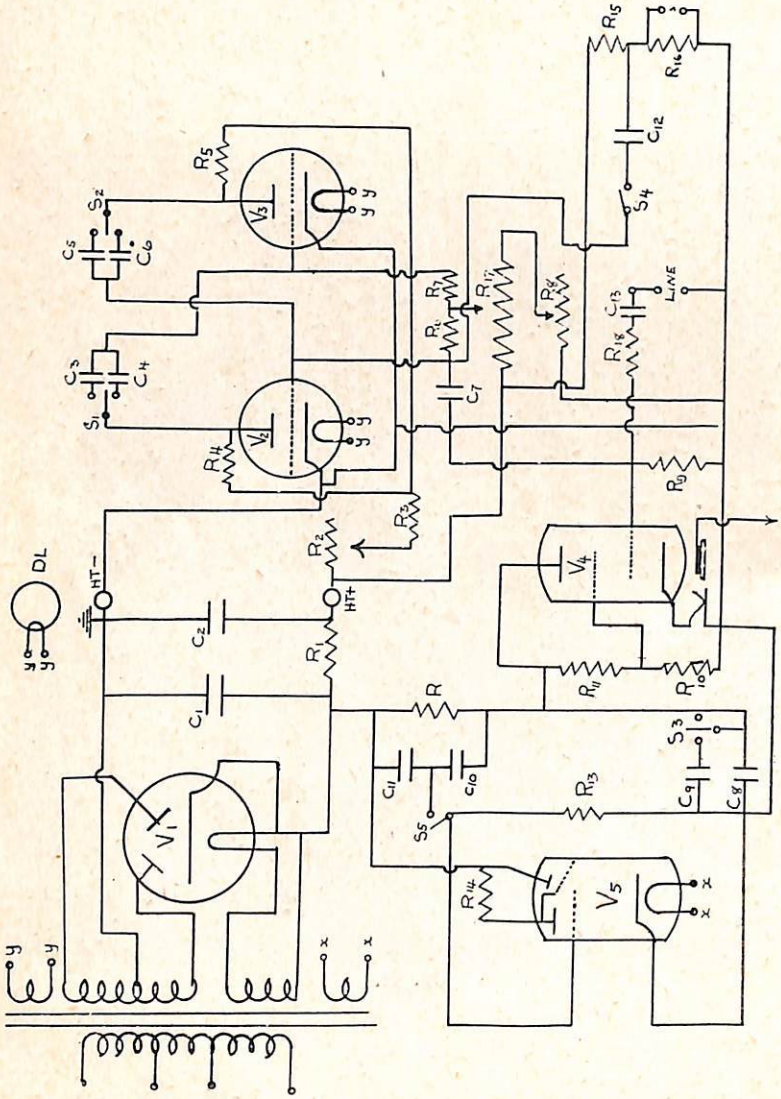


Fig. 34.

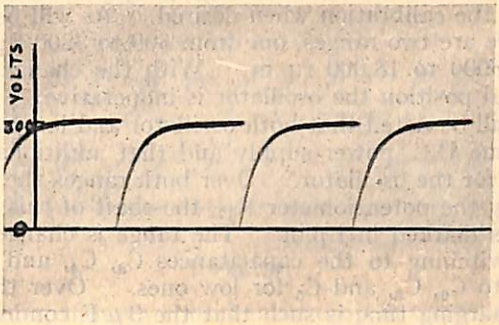


Fig. 35.

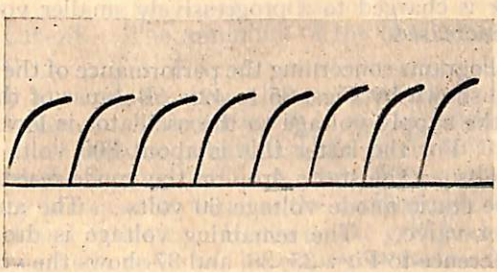


Fig. 36.

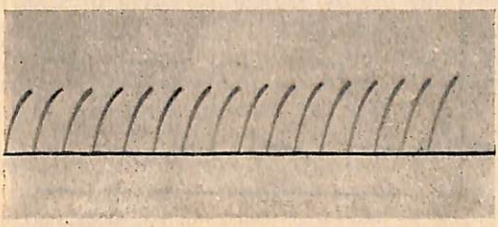


Fig. 37.

to 18,000 r.p.m. This instrument consists of a Neostron lamp, triggered by a multi-vibrator oscillator, a power unit, and means for checking the calibration when desired. As will be noted from Fig. 33, there are two ranges, one from 500 to 3200 r.p.m. and the other from 3000 to 18,000 r.p.m. With the change-over switch in the central position the oscillator is inoperative. Referring to Fig. 34, it will be noted that both oscillator and lamp are operated from the same D.C. power supply and that additional smoothing is employed for the oscillator. Over both ranges the frequency is controlled by the potentiometer R_{17}, the shaft of this carrying the dial which is marked in r.p.m. The range is changed by simultaneously switching to the capacitances C_8, C_4, and C_6 for high speeds and to C_9, C_3, and C_5 for low ones. Over the low speed range the charging time is such that the 3 μ F condenser is practically charged to the full voltage of the supply, *i.e.* 300 volts. Thus the integrated light output is approximately proportional to the flashing frequency. For the high speed range a 1 μ F condenser is employed in order to avoid overloading the lamp and also to ensure that the condenser shall be charged to an adequate voltage at the higher speeds. However, even with this reduction in capacity, the condenser is charged to a progressively smaller voltage as the frequency is increased.

Some oscillograms concerning the performance of the stroboscope of Fig. 32 are shown by Figs. 35 to 42. Because of the resistance R_1, Fig. 34, the supply voltage to the oscillator is lower than that to the lamp. For the latter this is about 300 volts and for the former 250 volts. The static drop on the anode resistances is 100 volts, and the static anode voltage 60 volts. The anode current is 1·0 Ma. per valve. The remaining voltage is dropped on R_2 and R_3. Reference to Figs. 35, 36, and 37 shows the voltage across the lamp at frequencies respectively corresponding to 3000, 6000, and 12,000 r.p.m. From Fig. 35, 3000 r.p.m., it will be noted that the condenser charges to the full voltage of the supply. This is also approximately the case in Fig. 36, 6000 r.p.m. Fig. 37, 12,000

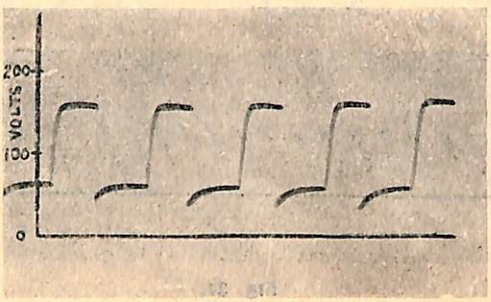


Fig. 38.

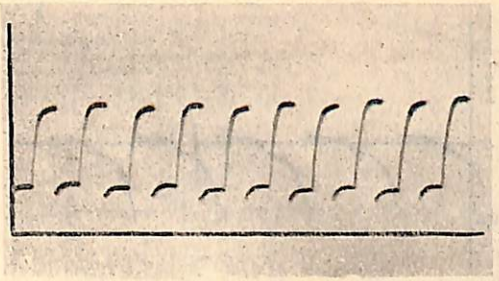


Fig. 39.

r.p.m., however, shows a considerable drop in condenser and lamp voltage, due to triggering occurring before the condenser has time to charge fully. Figs. 38 and 39 show the anode potential at 3000 and 6000 r.p.m., respectively. The sharp fall to a low positive potential at the moment the valve becomes re-conducting will be noted, also the rapid change to the static anode potential from this point. The high horizontal portion is, of course, where the anode potential attains a value equal to that of the H.T. supply at the moment of cut-off. The minimum of the oscillogram corresponds to v_1 in (52).

Figs. 40, 41, and 42 show the grid-cathode potential at the three speeds quoted. From Fig. 40 it will be noted that the grid has only a small positive potential while anode current is flowing. The fact that the figures shift in a generally negative direction as the frequency increases is because the oscillograph was connected between grid and cathode. Hence as the grid bias is made more positive the cathode potential becomes relatively negative. Thus the fall in the approximately horizontal portions of the figures is the amount by which the cathode goes negative (or the grid goes positive) as the frequency increases.

External Triggering.

In some cases it is desirable to trigger the tube by means of an external pair of contacts instead of by the oscillator. For example, if a rotating or reciprocating body is subject to uncontrolled fluctuations it will be difficult or impossible to obtain a steady impression. However, if a pair of contacts is fitted to the body these will open and close at precisely the same position in each cycle. Hence, if the contacts may be made to trigger the lamp, a steady impression will be received. In fact, even if the fluctuation were absent, the impression will be steadier than that obtained by means of the oscillator, owing to slight variations in the frequency of the latter. In the stroboscope of Fig. 34 external triggering is effected by means of the components R_{15}, R_{16}, C_{12}, S_4,

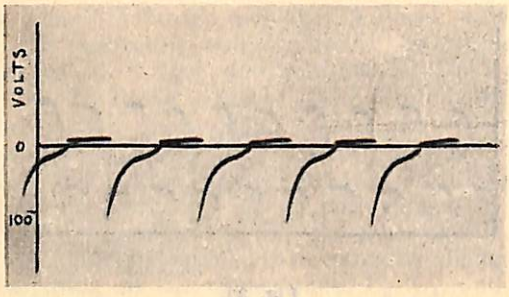


Fig. 40.

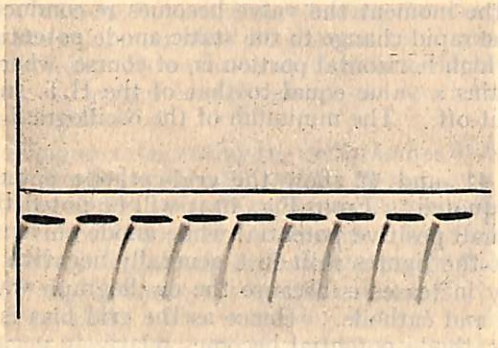


Fig. 41.

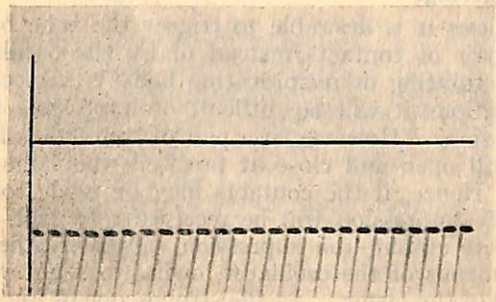


Fig. 42.

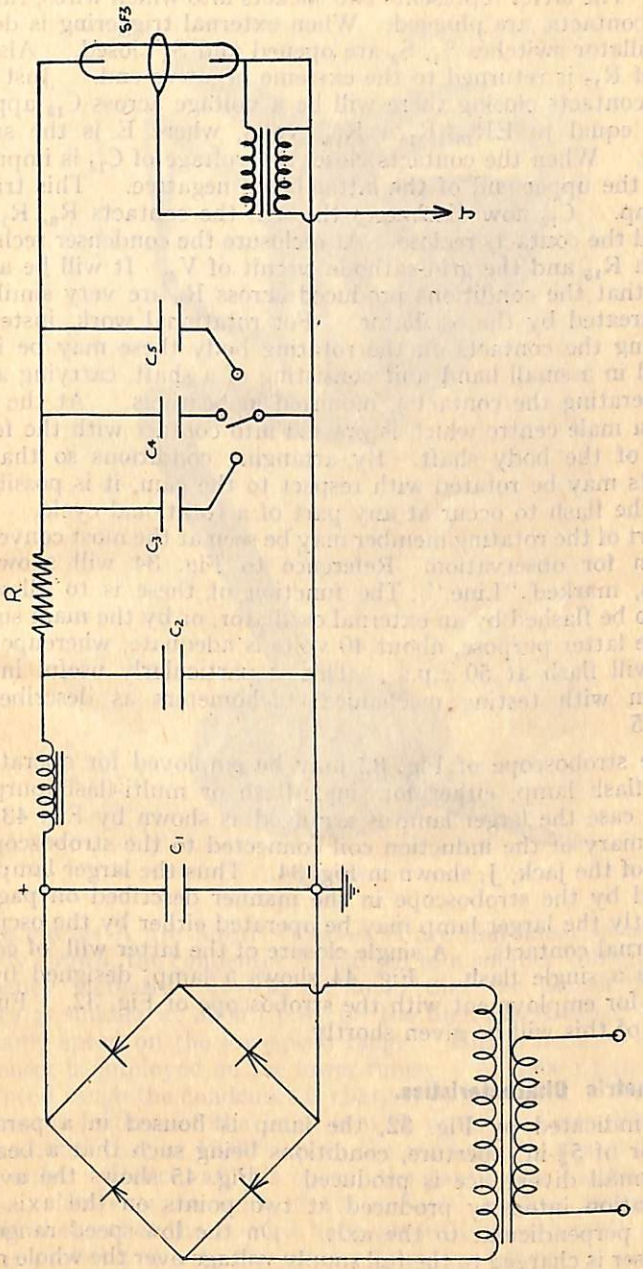


Fig. 43.

and *s*. The latter represents two sockets into which wires, running to the contacts, are plugged. When external triggering is desired the oscillator switches S_1, S_2 are opened and S_4 closed. Also the slider of R_{17} is returned to the extreme negative end. Just prior to the contacts closing there will be a voltage across C_{12} approximately equal to $ER_{16}/(R_{15} + R_{16})$ volts, where E is the supply voltage. When the contacts close, the voltage of C_{12} is impressed on R_9, the upper end of the latter being negative. This triggers the lamp. C_{12} now discharges through the contacts R_8, R_{17} and R_6 until the contacts reclose. At reclosure the condenser recharges through R_{15} and the grid-cathode circuit of V_2. It will be appreciated that the conditions produced across R_9 are very similar to those created by the oscillator. For rotational work, instead of mounting the contacts on the rotating body these may be incorporated in a small hand unit consisting of a shaft, carrying a cam (for operating the contacts), mounted in bearings. At the shaft end is a male centre which is pressed into contact with the female centre of the body shaft. By arranging conditions so that the contacts may be rotated with respect to the cam, it is possible to cause the flash to occur at any part of a rotational cycle. Thus any part of the rotating member may be seen at the most convenient position for observation. Reference to Fig. 34 will show two sockets, marked "Line." The function of these is to allow the lamp to be flashed by an external oscillator, or by the main supply. For the latter purpose, about 40 volts is adequate, whereupon the lamp will flash at 50 c.p.s. This is particularly useful in conjunction with testing mechanical tachometers as described on page 75.

The stroboscope of Fig. 32 may be employed for operating a larger flash lamp, either for single-flash or multi-flash purposes. In this case the larger lamp is arranged as shown by Fig. 43, and the primary of the induction coil connected to the stroboscope by means of the jack, J, shown in Fig. 34. Thus the larger lamp may be fired by the stroboscope in the manner described on page 37. Evidently the larger lamp may be operated either by the oscillator or external contacts. A single closure of the latter will, of course, provide a single flash. Fig. 44 shows a lamp, designed by the writer, for employment with the stroboscope of Fig. 32. Further details of this will be given shortly.

Photometric Characteristics.

As indicated by Fig. 32, the lamp is housed in a parabolic reflector of $5\frac{3}{4}$-in. aperture, conditions being such that a beam of fairly small divergence is produced. Fig. 45 shows the average illumination intensity produced at two points on the axis on a surface perpendicular to the axis. On the low-speed range the condenser is charged to the full supply voltage over the whole range.

Fig. 44.

Hence curves A are linear. Curves B are non-linear because, as already shown, the condenser is charged to a smaller voltage as the frequency increases. It will be noted that the illumination intensity is smaller at 3000 r.p.m. on the high-speed range than at the same speed on the low-speed range. This is because a larger condenser is employed on the lower range. At 3000 r.p.m. on the low-speed range the condenser is charged to 300 volts. Hence the continuous loading of the lamp is 6·75 watts. From Fig. 37 it will be noted that at 12,000 r.p.m. the condenser is charged to 230 volts only. Hence, at this speed, the continouus loading is 5·3 watts. However, in spite of the reduced loading, reference to Fig. 45 shows that the average light output is considerably greater. This is probably due to the greater luminous efficiency associated

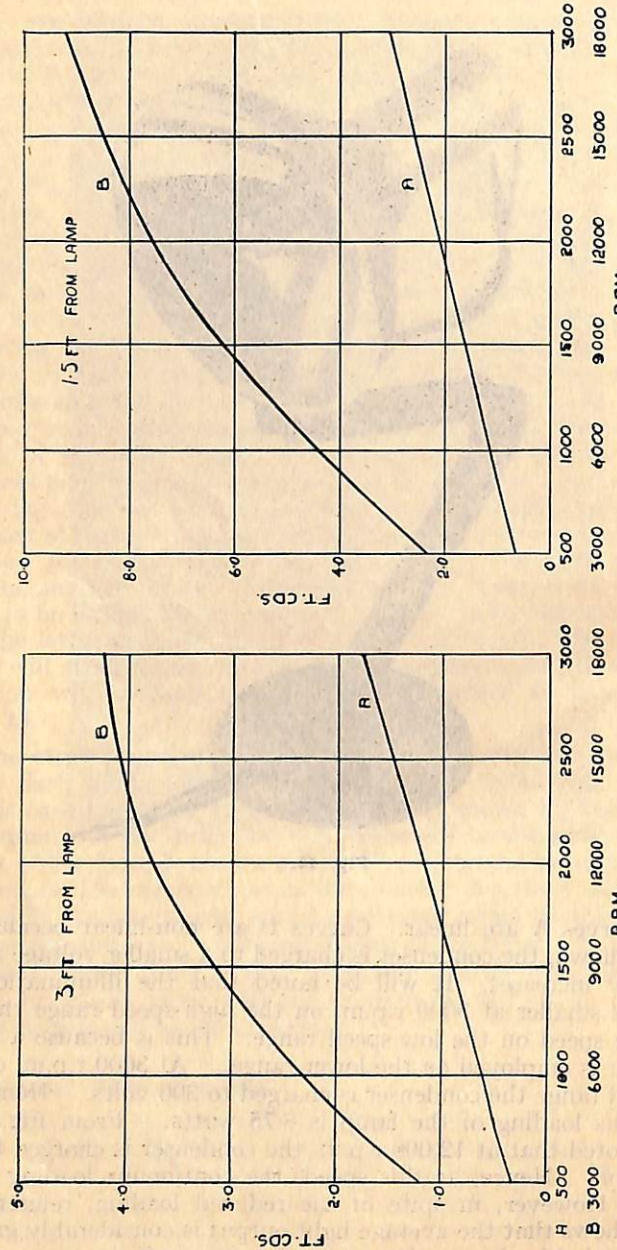

1·5 FT FROM LAMP
B
A
FT. CDS.
10·0
8·0
6·0
4·0
2·0
0
500
1000
1500
2000
2500
3000
3000
4000
9000
12000
15000
18000
R.P.M.
3 FT FROM LAMP
B
A
FT. CDS.
5·0
4·0
3·0
2·0
1·0
0
A 500
1000
1500
2000
2500
3000
B 3000
6000
9000
12000
15000
18000
R.P.M.

Fig. 45.

with the shorter discharge time of the smaller condenser. This feature is further demonstrated by comparing the performances at 3000 r.p.m. on the two ranges. In both instances the condensers are charged to the same voltage, but the energy storage of the smaller condenser is only one-third of that of the larger. Nevertheless, it will be noted that the light output is only about 50 per cent. greater on the low-speed range.

Arresting Properties.

Although the instrument of Fig. 32 was designed primarily for tachometry, it is of interest to consider its arresting properties. As indicated by (33) and Fig. 7, the current and light rapidly increase to maxima and thereafter fall slowly away. Hence it is indicated that a sharp impression of a moving object should be obtained, followed by a fainter impression due to the tail of the light curve. This means that some blurring may occur, the object appearing to subtend a greater angle than if complete arrest of motion were effected, the angular increase being in the direction of motion. Naturally these effects tend to be greater the higher the object speed. In order to study these effects, a white disc was attached to a high-speed motor. At radii of one and two inches radial and circumferential marks, 1/8-in. in length, were made with Indian ink. At 10,000 r.p.m. sharp impressions of the one inch marks were obtained followed by fainter impressions which could easily be discerned to be at least one and a half times the length of the sharp impressions. The fainter impressions were in the direction of motion and were due to the tail of the light curve. Naturally, the marks at the two-inch radius gave more pronounced effects than those at one inch. For complete arrest of motion at this speed it has already been deduced on page 4 that the discharge time should not exceed 5×10^{-6} sec. As the discharge time of the Neostron invariably exceeds this, it was to be anticipated that some slight blurring might occur. However, it is so slight as to be of negligible importance. From the apparent increase in the length of the 1-in. marks, the discharge time may be deduced. Thus taking the increase in length as $\frac{3}{16}$-in. gives the discharge time as 180 microsecs. However, the majority of this time is associated with the tail of the light curve and hence the latter results in only slight impressions.

Drift Adjustment.

Reference to Fig. 34 shows two small variable resistances R_2 and R_8. These are of the volume control pattern, the shafts being brought through the dial and marked "Drift Adjustment," Fig. 33. Their function is to enable the instrument calibration to be corrected should this change with the passage of time. It will be noted that R_2 is in series with the oscillator H.T. supply and R_8

with the grid biassing potentiometer R_{17}. Thus by variation of R_2 and R_8 voltages may be either added to or subtracted from the oscillator supply and bias voltages respectively. In order to indicate the state of calibration the cathode ray tuning indicator, V_5, Fig. 34, is employed. To the grid of this two voltages are fed, via R_{13}. One of these voltages is derived from the D.C. supply (ripple voltage) and the other from the lamp discharge condenser. Both voltages have extremely complicated waveforms, but, when the lamp is flashing at 50 c.p.s., the frequencies of the fundamentals of both are the same, *i.e.* 100 c.p.s. With the lamp flashing at some other frequency, a beat frequency is produced across R_{13} and the shadow angle opens and closes at this frequency. Actually the conditions on R_{13}, and on the grid of the tuning indicator, are extremely complicated owing to the complex nature of the voltage waves. However, the problem will be simplified by first considering the action of the fundamentals only.

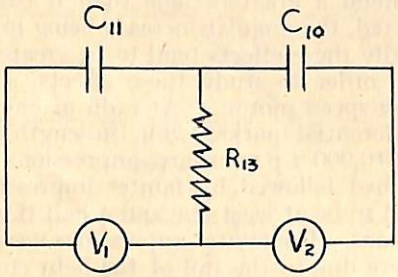


Fig. 46.

The essentials of the tuning circuit may be represented by Fig. 46, where $V_1 \sin p_1 t$ and $V_2 \sin p_2 t$ respectively represent the fundamentals of the voltages derived from the supply ripple and the discharge condenser. The sum of these two voltages is

$$V_1 \sin p_1 t + V_2 \sin p_2 t$$

and the alternating component on C_{11} is given by

$$\frac{C_{10}}{C_{10} + C_{11}} (V_1 \sin p_1 t + V_2 \sin p_2 t)$$

Hence the instantaneous potential difference across R_{13} is

$$v = V_1 \sin p_1 t - \frac{C_{10}}{C_{10} + C_{11}} (V_1 \sin p_1 t + V_2 \sin p_2 t) \quad (63)$$

on the assumption that the value of R_{13} is very high. Rewriting (63), we have

$$v = \frac{1}{C_{10} + C_{11}} (C_{11} V_1 \sin p_1 t - C_{10} V_2 \sin p_2 t)$$

and putting $p = p_1 - p_2$

$$v = \frac{1}{C_{10} + C_{11}} [C_{11} V_1 \sin (p + p_2) t - C_{10} V_2 \sin p_2 t]$$

$$= \frac{1}{C_{10} + C_{11}} [C_{11} V_1 \sin pt \cos p_2 t + C_{11} V_1 \cos pt \sin p_2 t - C_{10} V_2 \sin p_2 t]$$

$$= \frac{V}{C_{10} + C_{11}} [(C_{11} V_1 \cos pt - C_{10} V_2) \sin p_2 t + C_{11} V_1 \sin pt \cos p_2 t]$$

$$= \frac{V}{C_{10} + C_{11}} \sin (p_2 t + \theta)$$

where $V = \sqrt{C_{11}^2 V_1^2 + C_{10}^2 V_2^2 - 2 C_{10} C_{11} V_1 V_2 \cos pt}$

and $\theta = \arctan \dfrac{C_{11} V_1 \sin pt}{C_{11} V_1 \cos pt - C_{10} V_2}$

From this result it will be seen that the amplitude of the voltage across R_{13} varies at a frequency $p/2\pi = (p_1 - p_2)/2\pi$, *i.e.* the beat frequency. If the values of C_{10} and C_{11} are so chosen that

$$\frac{C_{11}}{C_{10}} = \frac{V_2}{V_1}$$

or $C_{11} V_1 = C_{10} V_2$

then $V = \sqrt{2}\, C_{11} V_1 \sqrt{1 - \cos pt}$

and $\theta = \arctan \dfrac{\sin pt}{\cos pt - 1}$

Hence, under these circumstances,

$$v = \frac{\sqrt{2}\, C_{11} V_1 \sqrt{1 - \cos pt}}{C_{10} + C_{11}} \sin (p_2 t + \theta)$$

and when $p = 0$ so also is v. Because of the numerous harmonics present in the waveforms, there are many other beat frequencies present, but these are generally higher than that due to the fundamentals. Hence it is easy to recognise the existence of the latter in the beating of the shadow angle.

To check the calibration of the stroboscope it is only necessary to set the dial to 3000 r.p.m. and observe the shadow angle. If this is seen to beat, the flashing frequency is different from 50 c.p.s. Hence either R_2 or R_8, or both, must be adjusted until no beat is observed. It is possible to check the calibration at certain speeds other than 3000 r.p.m. Thus at 6000 r.p.m. a beat effect may be produced between the second harmonic of the ripple voltage and the fundamental of the condenser voltage. Again, at 2000 r.p.m.

beats may be produced by the third harmonic of the condenser voltage and the fundamental of the ripple voltage.

A list of components for Fig. 32 is given by Table 3.

TABLE 3.

R_1	3,500 ohms	3 watt	C_1	8 μF	500 VW
R_2	30,000 ohms	1 watt	C_2	16 μF	500 VW
R_3	30,000 ohms	$\frac{1}{2}$ watt	C_3	0·02 μF	350 VW
R_4	100,000 ohms	2 watt	C_4	0·005 μF	350 VW
R_5	100,000 ohms	$\frac{1}{2}$ watt	C_5	0·02 μF	350 VW
R_6	1 megohm	1 watt	C_6	0·005 μF	350 VW
R_7	1 megohm	1 watt	C_7	0·0005 μF	350 VW
R_8	1500 ohms	1 watt	C_8	1 μF	350 VW
R_9	1 megohm	$\frac{1}{2}$ watt	C_9	2 μF	350 VW
R_{10}	10,000 ohms	$\frac{1}{2}$ watt	C_{10}	0·0005 μF	350 VW
R_{11}	50,000 ohms	$\frac{1}{2}$ watt	C_{11}	0·005 μF	350 VW
R_{12}	2,500 ohms	5 watt	C_{12}	0·10 μF	350 VW
R_{13}	1 megohm	$\frac{1}{2}$ watt	C_{13}	0·25 μF	350 VW
R_{14}	1 megohm	$\frac{1}{2}$ watt	V_1	43 IU Cossor	
R_{15}	50,000 ohms	$\frac{1}{2}$ watt	V_2	354 V Mullard	
R_{16}	100,000 ohms	$\frac{1}{2}$ watt	V_3	354 V Mullard.	
R_{17}	10,000 ohms	20 watt	V_4	NSP 1 Ferranti	
R_{18}	100,000 ohms	$\frac{1}{2}$ watt	V_5	Y 63 Osram	
			DL	Dial Light 4V. 2 watt.	

Reference has already been made to the lamp of Fig. 44 and the method of triggering this from the stroboscope. This lamp comprises an SF3 tube, housed in a 9-in. reflector, and operated from a 2000 volt supply. The induction coil is fitted at the back of the lamp, this resulting in a short connection from the coil to the triggering electrode. The coil primary and secondary windings respectively consist of 180 turns of 18G and 9000 turns of 42 G wire, wound on an open, laminated core. The turns ratio is thus 50 : 1, and, with an instantaneous voltage of 300 volts impressed on the primary, the secondary voltage is, approximately, 15,000 volts. Fig. 47 shows secondary voltage plotted against dial r.p.m. It will be noted that the voltage progressively decreases as the r.p.m. increases. This, of course, is due to the maximum condenser voltage decreasing as the oscillator frequency increases.

Referring to Fig. 43 it will be noted that three condensers are employed. One of these, 50 μF, is employed for single-flash work only. Of the other two, the 0·5 μF is employed on the low-speed range and the 0·15 μF on the high-speed range. Thus the lamp tends to be overloaded at the upper extremities of the ranges. However, this effect is slight because these extremities are seldom employed and, owing to the short charging time, the condenser fails to build to the full supply voltage thereat. In constructing a unit for single-flash work, it is advisable to employ

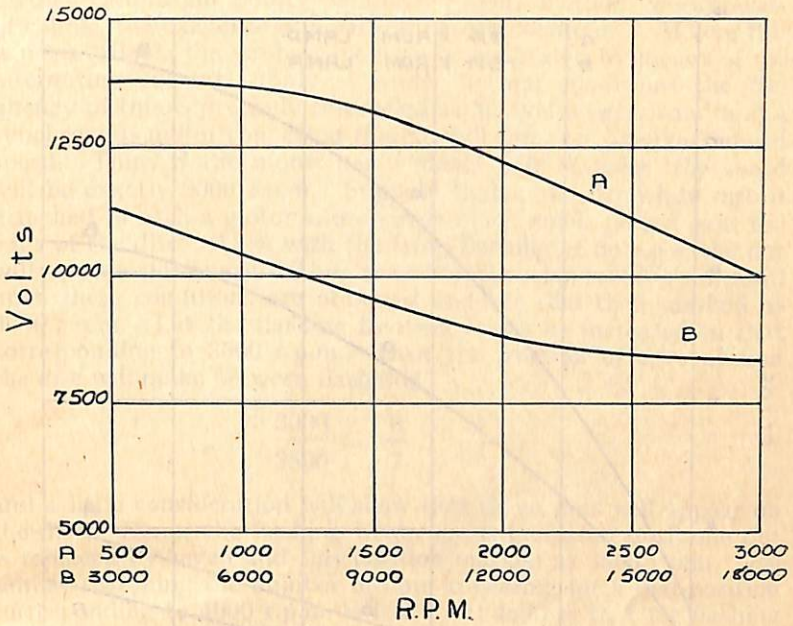


Fig. 47.

several small condensers in parallel to form the large capacitance required. A condenser breakdown is then likely to be less expensive than if a single unit is employed.

Photometric Characteristics.

Fig. 48 shows average illumination intensity curves at two points on the axis of the lamp of Fig. 43. Comparing these with those of Fig. 45, it will be noted that the intensity is not very much greater than in the latter case. However, in the former, both the area illuminated and the total light output are much larger. It will be observed that the change in intensity with distance along the axis is relatively small. This is due to the light beam being approximately parallel.

A list of components for Fig. 43 is given by Table 4.

TABLE 4.

R	10,000 ohms	25 watt	C_4	0·5 μF	2500 VW
C_1	8 μF	2500 VW	C_5	0·15 μF	2500 VW
C_2	8 μF	2500 VW			
C_3	50 μF	2500 VW	Supply 2000 V.60 MA.		

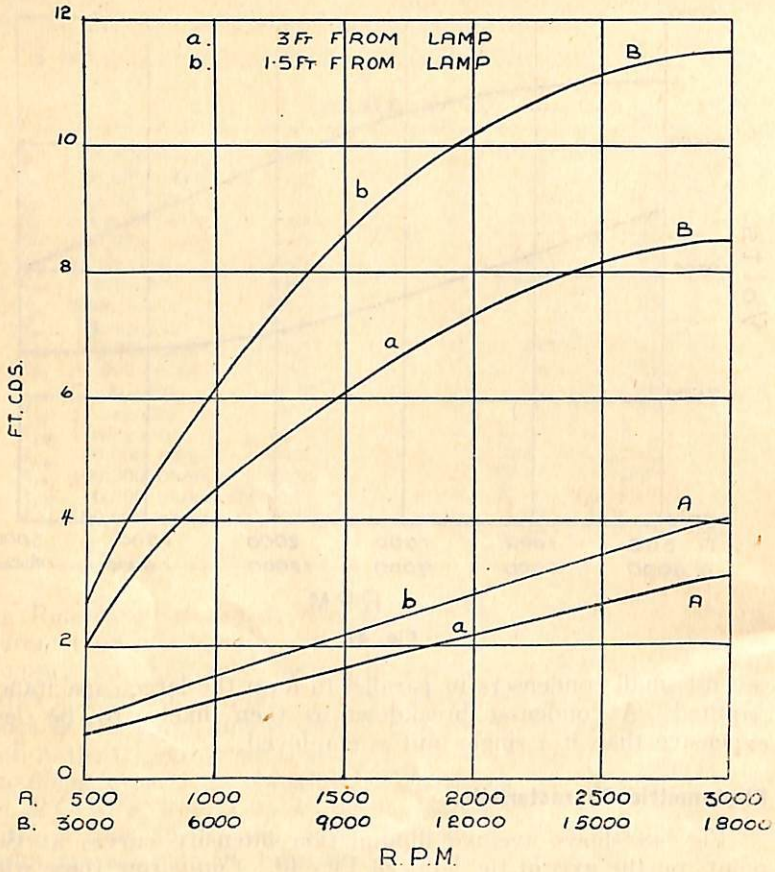


Fig. 48.

Tachometer Calibration.

Where a stroboscope is to be employed for cyclical speed measurement it must, of course, receive accurate calibration. The flashing frequency may either be determined by a separate frequency meter, operated from the oscillator or lamp circuit, or by precalibration of the oscillator. In the tachometer-stroboscope of Fig. 33 the latter method is employed, a dial attached to the rotor of the biassing potentiometer, R_{17}, Fig. 34, being marked in r.p.m. To calibrate, the lamp may be directed at a rotating body, the speed of which is accurately known, and the potentiometer adjusted until a stationary impression is obtained. The dial is then appropriately marked. The speed of the body is now changed and

further calibration points obtained. This method presupposes, of course, the existence of a substandard tachometer. Where this is not available the stroboscope may be calibrated by means of the alternating current supply. Under normal conditions the frequency of this is precisely controlled at 50 cycles per second and a synchronous motor connected thereto will run at a constant known speed. Thus, if the motor has a single pair of poles, the speed will be exactly 3000 r.p.m. Suppose that a circular white disc is attached to such a motor and a single black dot is placed near the edge of the disc. Then with the lamp flashing at 50 c.p.s. the dot will appear stationary. Thus the potentiometer rotor is adjusted until these conditions are obtained and the dial then marked as 3000 r.p.m. Let the flashing frequency now be increased to that corresponding to 3500 r.p.m. Then the fraction of a revolution the disc will make between flashes is

$$\frac{3000}{3500} = \frac{6}{7}$$

and a little consideration will show that seven dots will appear on the disc. Hence the flashing frequency is increased until one dot is replaced by seven and this position marked as 3500 r.p.m. By similar reasoning the number of dots appearing for a dial position corresponding to 4000 r.p.m. is four. It follows that for flashing speeds higher than 3000 r.p.m. the number of dots appearing is given by the denominator of the proper fraction

$$\frac{3000}{\text{r.p.m.}} \qquad (64)$$

when this is reduced to its lowest terms. For speeds lower than 3000 r.p.m. the number of dots appearing is still given by (64) but, of course, in this case the fractions are improper and for certain flashing speeds are integers.

It is evident that the denominator of (64) may be of such magnitude as to render the counting of the dots impracticable. To meet this difficulty a disc may be made on which, instead of a single dot, rings of dots are placed, the numbers per ring corresponding to high values of the denominator in (64). Then at the appropriate flashing speed a ring of dots will appear stationary and the dial may be marked accordingly. A disc, designed by the author, for calibrating the stroboscope of Fig. 33 is shown by Fig. 49.

The stroboscope of Fig. 33 is marked at every 100 r.p.m. on the low-speed range and at every 500 r.p.m. on the high-speed range. The number of dots for each speed is shown by Table 5. As it is difficult to count a number of dots exceeding ten, all numbers above this are marked on Fig. 49.

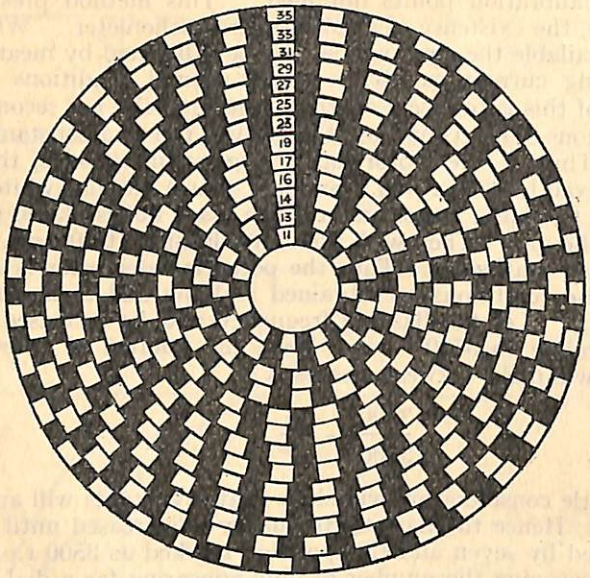


Fig. 49.

In calibrating it is advisable to commence from 3000 r.p.m. The correct flashing frequency for this speed will be attained at the highest value which gives a stationary effect for the entire disc. The speeds should next be marked corresponding to the low numbers in Table 5, using a single dot. The speeds corresponding to the high numbers may then be marked. In order to obtain clear impressions of the disc, it is essential that it be accurately divided and concentrically mounted.

As stated previously, it is possible to measure the flashing frequency by means of a frequency meter. A simple electronic frequency meter, designed by the author for use with the stroboscope of Fig. 33, is shown by Fig. 50. This has a stablished H.T. supply (by means of the neon tube V_1), the thyratron, V_2, being triggered by the volt drop on the resistance R_7, Fig. 34. If the condenser is charged to the full supply voltage before each discharge, then the quantity discharged through the ammeter at each flash is E_1C joules. Hence the current shown by the meter is

$$I = fE_1C \text{ amperes}$$

or

$$fE_1C \times 10^{-3} \text{ milliamps.}$$

when C is expressed in microfarads. It will be noted that the meter reading is proportional to the frequency and thus a linear

TABLE 5.

Low-Speed Range.

R.P.M.	No. of Dots.	R.P.M.	No. of Dots.
500	1	1,900	19
600	1	2,000	2
700	7	2,100	7
800	4	2,200	11
900	3	2,300	23
1,000	1	2,400	4
1,100	11	2,500	5
1,200	2	2,600	13
1,300	13	2,700	9
1,400	7	2,800	14
1,500	1	2,900	29
1,600	8	3,000	1
1,700	17	3,100	31
1,800	3	3,200	16

High-Speed Range.

R.P.M.	No. of Dots.	R.P.M.	No. of Dots.
3,000	1	10,500	21
3,500	7	11,000	11
4,000	4	11,500	23
4,500	3	12,000	4
5,000	5	12,500	25
5,500	11	13,000	13
6,000	2	13,500	27
6,500	13	14,000	14
7,000	7	14,500	29
7,500	5	15,000	5
8,000	8	15,500	31
8,500	17	16,000	16
9,000	3	16,500	33
9,500	19	17,000	17
10,000	10	17,500	35
		18,000	6

TABLE 6.

R_1	2,500 ohms	6 watt	C_1	0·1 μ F	250 VW
R_2	5,000 ohms	1 watt	C_2	0·5 μ F	250 VW
R_3	2 megohms	$\frac{1}{2}$ watt	C_3	0·005 μ F	350 VW
M	0-4 Milliamps.,	Moving Coil.	C_4	0·005 μ F	
			V_1	S 130	Cossor
			V_2	GTIC	Osram
			E_1	140 volts	
			Eg	15 volts	
			E	240 volts.	
			T	1 : 1	

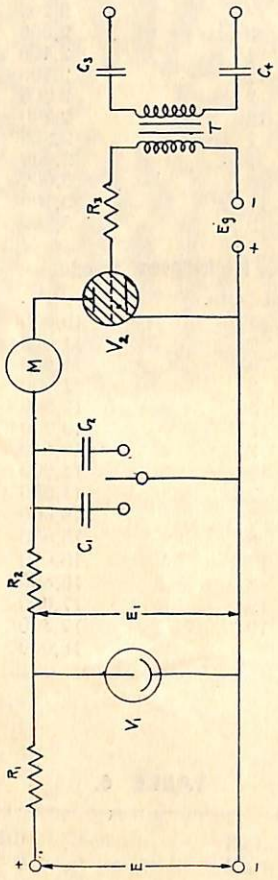


Fig. 50.

scale results. The range of the meter may, of course, be changed by changing the value of C. The values and details of the components of Fig. 50 are given by Table 6.

As an alternative to a separate frequency meter, it is possible to include an ammeter in the condenser charging circuit of Fig. 34. This meter may then read either the average or r.m.s value of the charging current, these values being respectively given by (17) and (18). As these currents are functions of frequency, the meter may be calibrated in terms of frequency. A disadvantage of this method is that a change in the value of E affects the meter calibration.

Applications of the Electronic Stroboscope.

The general applications of the electronic stroboscope have been indicated in the introductory remarks. The particular applications are so numerous that it is impossible to give more than a brief account of these. However, among the latter the following studies may be mentioned:—

COMBUSTION ENGINES.
Vibration, valve operation, ignition timing, gear meshing, etc.

AIRCRAFT.
Similar studies as with combustion engines, also propeller whip.

ELECTRICAL ENGINEERING.
Contact breaker bounce, standing waves on loud speaker cones, hunting, induction motor slip, brush bounce, etc.

MACHINERY.
Critical speeds, dynamic balancing, governor operation, gear cutting angles, h.p. determination through measurement of angle of torsion meter, cams, shuttles, couplings, tapping operations, fans, etc.

Mechanical Tachometer Calibration and Checking.

In this application the stroboscope is flashed at line frequency and a disc, similar to that of Fig. 49, fitted to the tachometer shaft. By varying the speed of the shaft until a particular ring is stationary, the speed can be determined and the tachometer dial marked or checked with an accuracy which is solely dependent on that of the

supply frequency. For a single dot, the number of dots appearing on the disc is given by the denominator of the fraction

$$\frac{\text{r.p.m.}}{3000}$$

when this is reduced to its lowest terms.

Photography.

The photography of high-speed objects is in some ways analogous to photography with cathode ray oscillography. For example, a stationary effect can be obtained of some cyclical phenomenon with a stroboscope, and a relatively long exposure then made. This, of course, corresponds to photography of a standing image in oscillography. However, simple stroboscopes are seldom used for anything beyond ordinary visual observation, photography, generally, being effected with a single-flash circuit. In the latter case non-cyclical as well as cyclical phenomena can be recorded, this corresponding to photography of transients on an oscillograph screen. In practically all cases there is nothing which can compare with the single-flash lamp for high-speed work with its high illumination intensity lasting for a few microseconds only. By this means, motions of projectiles and living creatures may be recorded and information obtained which would otherwise be impossible of attainment. An important application of the flash lamp is the production of motion-pictures, but more will be said of this after dealing with methods of obtaining single shots.

Although the most valuable application of the single-flash circuit is the photography of of high-speed phenomena, it must be mentioned that this circuit is now frequently employed for the photography of stationary and slowly moving subjects. In the former of these cases the subject is sometimes focused in subdued light, the camera shutter then opened, the lamp flashed, and the shutter then reclosed. This method is extremely simple, but has the disadvantage of requiring a darkened room. An alternative method, and one suitable for slowly-moving subjects (*i.e.* subjects, the motion of which is such that they come within the scope of ordinary shutter speeds) is to synchronise the shutter opening with the lamp flash. This may be effected by causing the shutter cocking lever to make contact with an insulated strip spring as it passes through its mid-position on release. The spring may be mounted on the lens board or support, as shown by Fig. 51. Two insulated wires are led from the spring and shutter to the grid and cathode of the triggering tube in a circuit such as that of Fig. 20. The size and insulation of the wires need be only slight as the power involved is negligible and the voltage small. In order to determine the mid-position of the shutter, it should be set to the lowest speed

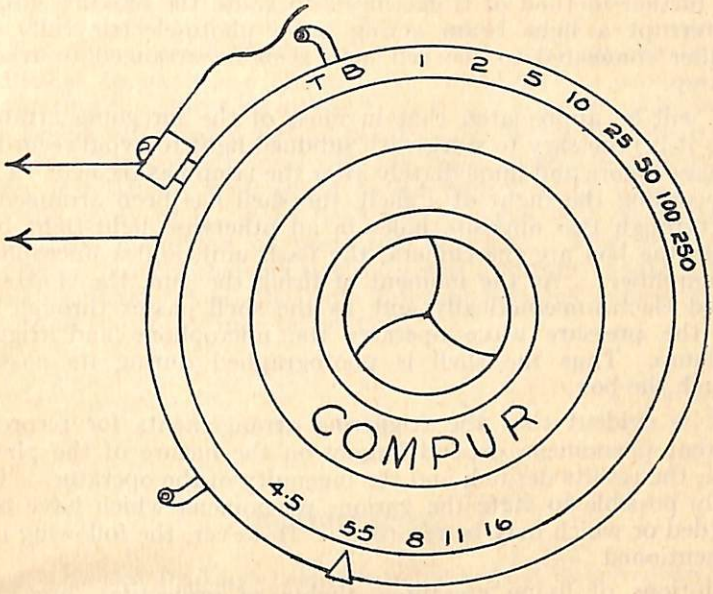


Fig. 51.

available, say, one second, the cocking lever held, the release mechanism then operated while the cocking lever is slowly lowered under finger restraint. The mid-position will then be readily determined. For normal operation the shutter should be set to the highest speed of which it is capable.

For studying the effects of shattering objects, due to falling, it is possible to cause the falling object to close two contacts, thus operating the triggering circuit. For example, the object may be caused to strike the upper of two metal plates which are separated by crumpled pieces of paper at their edges, the plates, of course, forming the contacts. In this case the camera shutter is opened immediately prior to the fall and closed immediately after. Evidently the normal lighting must be subdued during the actual operation.

Where some phenomenon to be recorded is accompanied by sound (*e.g.* the flight of a projectile) the latter may be employed to trigger the lamp by operating through a microphone and amplifier. Thus the flights of bullets and shells may be photographed by causing the firing explosion to trigger the lamp. By placing the microphone at different distances from the gun, the time between the explosion and triggering may be controlled. Thus a succession of photographs of some phase of a repetitive action may be obtained by shifting the microphone position between each flash.

A further method of triggering is to cause the moving subject to interrupt a light beam acting on a photo-electric cell. An amplifier connected to the cell may then be arranged to trigger the lamp.

It will be appreciated that in most of the foregoing arrangements it is necessary to work with subdued light to avoid recording an image before and immediately after the lamp has flashed. Thus for recording the flight of a shell, the shell has been arranged to pass through two opposite holes in an otherwise light-tight box. Within the box are the camera, the flash unit, and a microphone and amplifier. At the moment of firing the gun, the shutter is opened electro-magnetically and, as the shell passes through the box, the pressure wave operates the microphone and triggers the lamp. Thus the shell is photographed during its passage through the box.

It is evident that the triggering arrangements for recording different phenomena depend largely on the nature of the phenomena, the results desired, and the ingenuity of the operator. It is hardly possible to state the various phenomena which have been recorded or which may be recorded. However, the following may be mentioned :—

Motions of living creatures, flights of projectiles, breakages under impact, shaft and propeller whip, surface tension phenomena accompanying splashes, cavitation, liquid turbulence, fuel atomisation, etc., etc. For some of the photographic possibilities of the single-flash circuit the reader is advised to consult Edgerton and Killian's book "flash."

Stroboscopic Photography.

For purely cyclical phenomena the stroboscope gives eminently satisfactory results, whether employed for visual examination or relatively long-exposure photography. For slow transients superposed on a cyclical base, the stroboscope will often give satisfactory results, while a single aspect of a transient may be obtained with an ordinary camera and a single-flash circuit. Where high-speed transients occur, detailed information of these may be obtained from a series of photographs, each taken at a short interval after each other. These photographs are subsequently examined in series or projected in slow motion. This process, *i.e.* series photography and subsequent projection, corresponds to slow-motion cinematography and is termed stroboscopic photography.

For ordinary cinematograph work, photography is carried out at 16 to 24 frames per second, each frame being mechanically synchronised with the shutter operation. For stroboscopic photography much higher speeds are employed, in some instances as high as 4000 frames per second. These speeds are effected by

moving the film at high speed past the lens, the latter remaining open while the film is running. The speed of the film is invariably so high that normal indoor light, received through the lens, is insufficient to have any effect. The exposures are produced by illuminating the object by a flash lamp which is triggered by means of an accurately constructed contactor, mounted on the film driving sprocket. The power required by the lamp for this form of photography is relatively high owing to the high flashing rate. Apart from the study of transient behaviour, stroboscopic photography permits the deduction of projectile velocities. This is effected from two exposures showing two images at a distance apart. Then from this distance and the time interval between exposures the velocity of the object may be deduced.

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